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THE PHYSICS OF ELECTRON TUBES

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THE PHYSICS OF ELECTRON TUBES

BY

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TO
N. M. K.

PREFACE

It is the aim of the author in writing this book to present the fundamental physical phenomena involved in the operation of electron tubes. The emphasis has been placed on what goes on within the tube and not upon the external conditions. Vacuum-tube circuits and applications have been amply discussed elsewhere.

The writer has tried to present the subject from the point of view of a physicist in such a fashion that it will be of interest to engineers and to students of physics who have no special training in electronics.

A short course given in the Massachusetts Institute of Technology during the summer of 1931 formed the basis for the book.

The writer has drawn freely upon all the available published sources of information. In giving references, no attempt has been made to provide a complete bibliography. In many instances, the references cited are not the original sources, but they have been chosen because they summarize the material in a convenient form and are accessible to the majority of students. This is particularly so in the case of the monographs by Langmuir and Compton and Compton and Langmuir on "Electrical Discharges in Gases," and by Dushman on "Electron Emission" published in the *Reviews of Modern Physics*.

The writer wishes to express his appreciation to Mrs. M. R. Andrews and Dr. A. W. Hull, who read the manuscript and made many valuable constructive suggestions. He also wishes to acknowledge his debt to Dr. S. Dushman and his other coworkers in this labora-

tory, to whom he owes much of his knowledge of the subject.

He wishes to thank Dr. B. T. Barnes, of the Nela Park Laboratory, for the microphotograph of Fig. 7 and Mr. L. L. Wyman, of this laboratory, for those of Figs. 25, 26, and 27.

L. R. KOLLER.

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THE PHYSICS OF ELECTRON TUBES

CHAPTER I

THEORY OF THERMIONIC EMISSION

1. Thermionic Emission and the Electron.

A precise knowledge of the behavior of electrons is the basis of the entire art of radio communication as well as of many other practical applications of vacuum tubes. Electrons (in the sense in which the word is used today) were unknown as recently as 1895. For over two hundred years it had been known that air in the neighborhood of incandescent solids possessed certain peculiar electrical properties, such as that it was no longer a good insulator and that it caused charged bodies to lose their charge. No headway was made toward a comprehensive theory of this peculiar behavior until Sir J. J. Thomson and others showed that the charges emitted by hot bodies were identical with those emitted from solids under the influence of ultraviolet light or those observed in cathode rays. Through the work of many investigators it was finally established that all of these charges were identical, *i.e.*, electrons.

We now know that all matter is made up of a number of simple units and that different kinds of matter differ only in the number and arrangement of these units. The simplest of these units is the electron or unit negative electrical charge. Its magnitude is

$$4.77 \times 10^{-10} \text{ e.s.u.}$$

or

$$1.591 \times 10^{-19} \text{ amp.-sec.}$$

Electrons may be freed from matter by various agencies, such as heat, light, impact of other electrons, intense electric fields or x-rays. The functioning of all vacuum tubes depends first of all on one or more of these processes and then upon the behavior of the electrons when they have been freed from matter and pass out into space. In all types of vacuum tubes electrons are caused to escape from one electrode, to pass across an intervening space and to enter another electrode. This chapter will deal with the liberation of electrons from the surface of the cathode.

The most common method of causing the liberation or emission of electrons is by heating. This phenomenon is commonly known as *thermionic emission*. While the complete theory is the work of a large number of investigators, the foundation was laid by O. W. Richardson.

The very earliest observations of thermionic emission were those of the peculiar behavior of air in the neighborhood of charged bodies. The phenomena, however, are extremely complicated at atmospheric pressure, and little progress was made until they were studied *in vacuo*.

2. The Edison Effect.

In 1883 Thomas Edison made a significant discovery of what came to be called the *Edison effect*. He observed that when a third electrode was placed inside an incandescent lamp, between the two filament leads, and was connected to the positive terminal of the filament through a galvanometer, as shown in Fig. 1, a current passed through this circuit. When the connection was made to the negative filament terminal, no such current was observed. What Edison had found was a true electron current. Electrons were emitted from the surface of the

hot filament and were collected by the auxiliary electrode, provided that this electrode was at a positive potential with respect to the filament (or the part of the filament from which the electrons were emitted). Fleming investigated this effect at great length, and Elster and Geitel, who later were pioneers in the field of photoelectricity, made similar investigations.

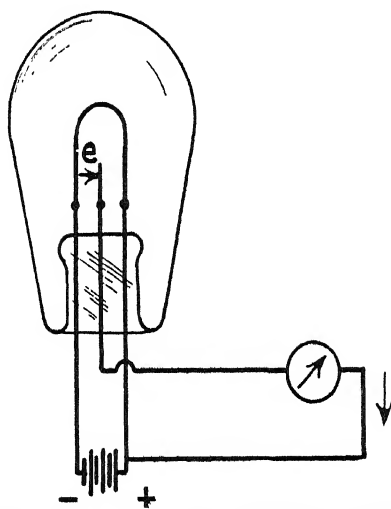


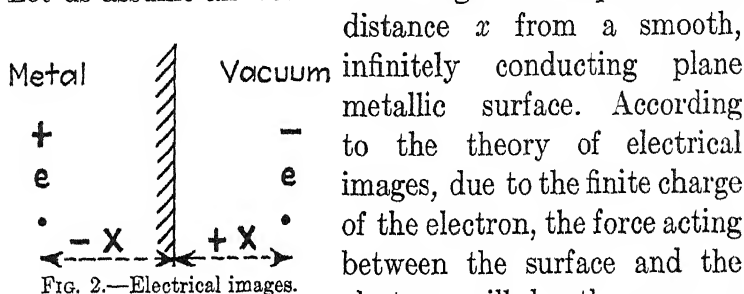
FIG. 1.—The Edison effect. The arrow indicates the direction of electron flow.

This Edison effect was not clearly understood, however, until the work of Thomson established the fact that the charges emitted by hot bodies were electrons. It remained for Richardson to derive the quantitative relationship between the number of electrons emitted and the temperature of the hot body.

3. Electrical Images and the Work Function.

According to the theory of the conduction of electricity in metals all conductors contain a huge swarm of electrons in constant random motion, much like the molecules of a gas. These electrons are called *free electrons*. It is evident that strong forces must be acting

to prevent the emission of these electrons, otherwise a small voltage applied to the anode of a tube would lead to a large flow of current from the cathode. The forces which prevent the escape are the electrical image forces. Let us assume an electron of charge e to be placed at a



distance x from a smooth, infinitely conducting plane metallic surface. According to the theory of electrical images, due to the finite charge of the electron, the force acting between the surface and the electron will be the same as if an equal charge of opposite sign were induced at an equal distance behind the surface, as shown in Fig. 2. The force acting between these two charges would then be

$$F = \frac{e^2}{4x^2} \quad (1)$$

If this charge be moved through a small element of distance dx , the work done upon it is

$$dw = \frac{e^2}{4x^2} dx \quad (2)$$

The work done in removing the charge to a distance x from the metal would be

$$W = \int_0^x \frac{e^2}{4x^2} dx \quad (3)$$

For very small values of x this integral would become infinite. This is not in accordance with the experimental facts, however, as electron emission could never take place at all if it required an infinite amount of work to remove an electron. The difficulty is due to the assumption that the inverse-square law of attraction

between charges (which is valid for macroscopic distances) applies here. It probably gives place to some other law of force when we are dealing with distances of the order of atomic dimensions. Equation (3) then becomes

$$W = W_0 + W_1 \quad (4)$$

where W_0 represents the work done in bringing the electron from the surface of the metal to a distance x_1 from the surface against a force following some unknown law, and W_1 represents the work done in moving the electron from x_1 to infinity against a force following the inverse-square law. It has been shown by Langmuir that the value of W does not depend greatly on the particular assumption as to the law of force, which we assume to hold within the distance x_1 , the total work W being always very nearly

$$W = \frac{e^2}{2x_1} \quad (5)$$

where the distance x_1 is a characteristic of the particular metal involved. W then represents the work done by a single electron in escaping from the surface of a metal. Instead of expressing this work in mechanical units, such as foot-pounds or ergs, it is more convenient to express it in electrical units as the product of the charge e and the potential difference through which it would have to move to do an amount of work W , *i.e.*,

$$W = e\phi \quad (6)$$

The quantity $W/e = \phi$ (the work per unit charge) is called the *work function* and is proportional to the work done by an electron in escaping from the surface. The work function is a definite quantity which is characteristic for each substance. It is usually expressed in volts. The values which are met with in practice vary

from about 1 volt to 10 volts. Referring to Table I, Column II gives values for a number of commonly used elements.

Since $\phi = W/e = e/2x_1$, if we know ϕ , we can calculate x_1 . It has been found that x_1 is of the same order of magnitude as the atomic radius. In general, the lower the value of ϕ the greater is x_1 , or, conversely, the substances having the largest atomic radii have the smallest values of ϕ , *i.e.*, it is easier for electrons to escape from substances having large atomic radii. This serves as one criterion for the choice of suitable electron emitters. The values of the atomic radii for a number of the elements are given in the last column of Table I. From this table it can be seen that the elements with the largest atomic radii are those with the smallest values of work function.

According to the theory just developed, an electron cannot escape from a metal surface unless it has sufficient energy to overcome the forces at the surface. Its kinetic energy must be in excess of

$$W = \phi e$$

4. Richardson's Equation.

The free electrons within the metal may be treated as if they were molecules of a fluid. Presumably they move in random directions with various velocities. There are a very few very slow moving ones and a few extremely fast moving ones and others with all possible velocities in between. The number of electrons having velocities between any two limits v and $v + dv$ is determined by *Maxwell's distribution law*. This number is a function of the temperature. The higher the temperature the larger will be the percentage of the total number of electrons having velocities exceeding any given value. At low temperatures only a relatively few electrons will

have velocities in excess of the amount necessary to give them sufficient energy to overcome the retaining forces at the surface. In order to escape they must have velocities such that

$$\frac{1}{2}mv^2 \geq W \quad (7)$$

The higher the temperature the larger will be the fraction of the total number of free electrons which will be able to satisfy this requirement. Accordingly, the higher the temperature the more electrons will escape, so that thermionic emission increases with increasing temperature.

Richardson derived a quantitative relation for the number of electrons emitted as a function of temperature based on these considerations. This expression is

$$I = a\sqrt{T}\epsilon^{-b/T} \text{ (For derivation see Appendix A)} \quad (8)$$

where I = amperes of electron current per square centimeter of cathode surface

$*T$ = absolute temperature

a and b = constants for any given material

ϵ = Napierian base.

From this expression it is evident that the electron emission for any given substance increases very rapidly with temperature. Since the term b is proportional to the work function, it can also be seen that for different materials at the same temperature the emission is larger the smaller the value of the work function. This expression is most conveniently used in the form

$$\log \frac{I}{\sqrt{T}} = \log a - \frac{b}{2.303T} \quad (9)$$

A plot of $\log I/\sqrt{T}$ against $1/T$ will give a straight line having a slope $b/2.303$ and an intercept $\log a$.

* Absolute temperature in degrees Kelvin equals temperature in degrees Centigrade + 273.

The relation between b and ϕ is

$$b = \frac{\phi e}{K} \quad (10)$$

where K is the Boltzmann constant. On substituting numerical values we find

$$b = \phi \times 11,600 \quad (11)$$

where ϕ is expressed in volts.

5. Dushman's Equation.

Richardson suggested another form for his equation. Later Dushman derived the same form, basing his derivation on thermodynamic considerations. This equation is

$$I = AT^2 e^{-b_0/T} \quad (12)$$

This equation can also be expressed in the form

$$\log \frac{I}{T^2} = \log A - \frac{b_0}{2.303T} \quad (13)$$

which is the equation of a straight line with ordinates $\log I/T^2$ and abscissae $1/T$.

The slope of this line is $b_0/2.303$. In this case A is a constant which is the same for all pure metals, and b_0 differs from b in that

$$b_0 = \frac{\phi_0 e}{K} \quad (14)$$

where ϕ_0 is the work function at the absolute zero. From a practical standpoint this equation is more convenient to use since we can determine b_0 from a single observation. A has the value 60.2 for all pure metals. Table II gives some values for b_0 for various filament

materials. The relation between b_0 and the b of Richardson's equation is

$$b = b_0 + \frac{3}{2}T \quad (15)$$

Either form of the equation fits the experimental facts equally well since the slope of the curve is chiefly determined by the exponential term, but the form of Eq. (12) is more convenient and will be used throughout this book. This equation is of great importance in vacuum-tube design.

6. Experimental Determination of Constants.

The simplest and most direct method of determining b_0 is by experimental measurement of values of emission at various temperatures. b_0 can then be calculated from the slope of the $\log I/T^2$ against $1/T$ plot. Once the value of b_0 is known, the emission per unit area of filament surface at any temperature can be calculated or, if the filament area is fixed, the temperature required to give a definite value of emission, etc.*

Figure 3 gives experimental values of emission from a tungsten filament at different temperatures and a plot of the data from which b_0 is calculated.

Values of the work function have also been obtained by a calorimetric method. This method is based on the analogy between the thermionic emission of electrons

* For example: What will be the emission from a tungsten filament 10 cm. long and 0.025 cm. in diameter at a temperature of 2200°K.?

Filament area = $2\pi rl = 2\pi \times 0.0125 \times 10 = 0.786$ sq. cm.

For tungsten, $b_0 = 52,400$ (from Table II)

$$A = 60.2$$

$$I = AT^2e^{-b/T}$$

$$= 60.2 \times (2200)^2 e^{-52,400/2200} = 0.1324 \text{ amp. per square centimeter of filament surface.}$$

Therefore,

$$i = 0.1324 \times 0.786 = 0.1042 \text{ amp.}$$

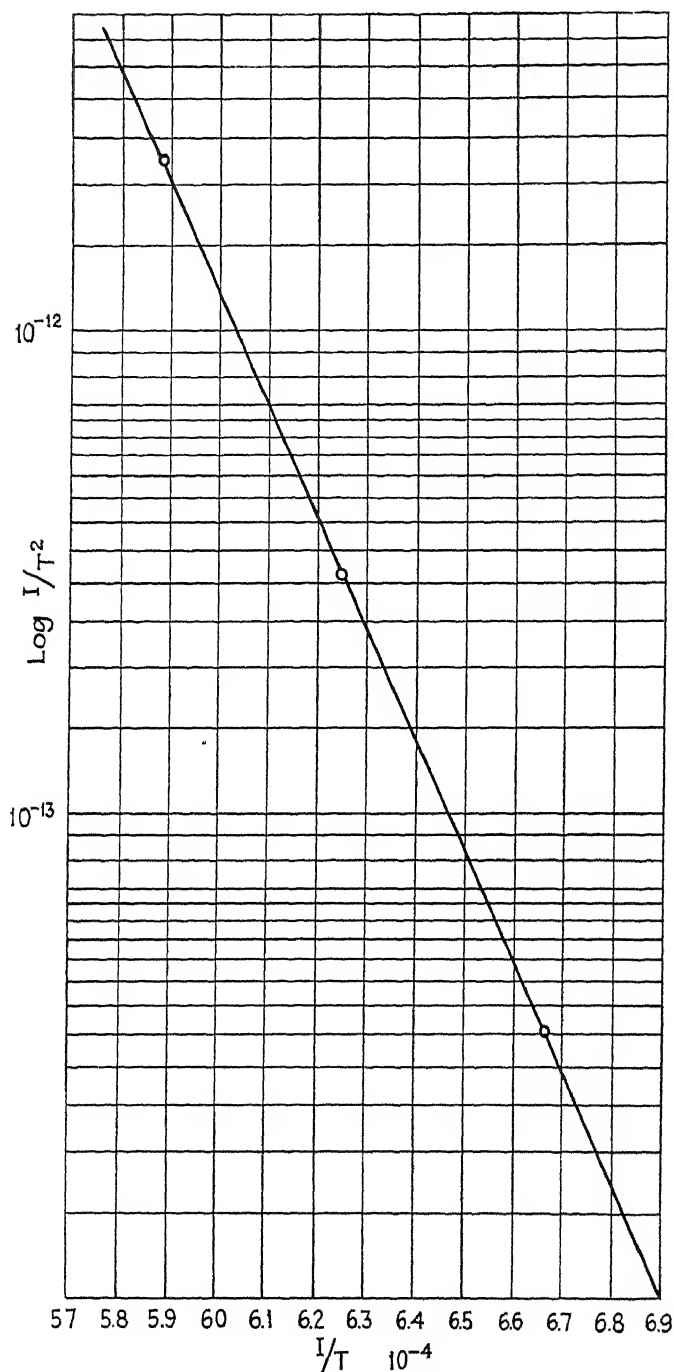


FIG. 3.—Plot of the emission equation for tungsten from the experimental data given on page 11.

and the evaporation of molecules from the surface of a liquid. The heat of evaporation of the electrons is analogous to the latent heat of evaporation of the molecules from the liquid. The work done in transporting an electron across the surface of the metal, *i.e.*, the latent heat of evaporation per electron, is ϕe . This energy is derived from the thermal energy of agitation of the electrons within the metal. Accordingly the emission of electrons from a metal results in a cooling of the metal. Davisson and Germer made use of this fact to determine the work function of tungsten. They measured the energy input to a filament, with the usual anode made negative, *i.e.*, with no electrons escaping from the filament. They then made the anode positive so that an electron current i passed, and again measured the energy input to the filament. The difference in energy input required to maintain the filament at the same temperature as before represented the heat of evaporation of the electrons:

$$E = ne\phi \quad (16)$$

The value of ϕ determined by this method is in excellent agreement with that obtained by other methods.

EXPERIMENTAL DATA FOR THE PLOT OF FIG. 3

T°, K	$1/T$	i	I	I/T^2
1500	0.666×10^{-3}	8.0×10^{-9} amp.	8.0×10^{-8} amp./cm ²	3.55×10^{-14}
1600	0.625×10^{-3}	8.0×10^{-8}	8.0×10^{-7}	3.13×10^{-13}
1700	0.588×10^{-3}	6.5×10^{-7}	6.5×10^{-6}	2.25×10^{-12}
1800	0.556×10^{-3}	4.0×10^{-6}	4.0×10^{-5}	1.28×10^{-11}

Filament area = 0.1 sq. cm.

$$I = AT^2 e^{\frac{b_0}{T}}$$

$$\log I/T^2 = \log A - b_0/2.303T$$

$$b_0 = \frac{\Delta \log I/T^2}{\frac{1}{2.303T}} = \frac{2.303}{0.438 \times 10^{-4}} = 52,600$$

Owing to the large effect of the b_0 term in the emission equation, b_0 serves as a good indicator of the relative emitting powers of different materials. The lower the value of b_0 the higher the emission at any given temperature.

The effect on the emission of a small change in temperature is given by

$$\frac{dI}{I} = \left(\frac{b}{T} + 2 \right) \frac{dT}{T} \quad (17)$$

Thus in the case of thoriated tungsten ($b_0 = 30,500$) a 1 per cent change in temperature at $T = 2000^\circ\text{K}$. will result in approximately a 17.25 per cent change in emission. Accordingly it is of great importance to be able to determine temperature accurately and to be able to maintain it constant in making emission measurements. Thermionic emission has a larger temperature coefficient than any other physical property of matter except vapor pressure. It has been suggested for this reason that thermionic emission be used as a measure of temperature.

7. The Schottky Effect.

So far we have not considered the effect of the accelerating field due to the anode voltage but have considered only the electrical image forces. This accelerating field is of course acting in opposition to the electrical image force. At some distance x_0 from the cathode the two fields must just balance each other. Nearer the cathode the image force predominates, and nearer the anode the external field predominates. Any electron with sufficient energy to reach this critical plane can escape. The greater the field due to the anode, the nearer to the cathode will the critical surface lie and accordingly electrons with smaller initial velocities will be able to reach this plane and escape. The result is that the

voltage applied to the anode has a slight effect on the work which an electron must do to escape, *i.e.*, on the work function. By lowering the work function this field makes it possible for electrons, which would not otherwise be able to do so, to escape. The result is that there is an increase in emission with increasing anode voltage. This effect is not large for ordinary voltages. Its magnitude has been calculated by Schottky; hence it is known as the *Schottky effect*. The formula derived by Schottky is

$$i = i_s e^{4.389 E^{1/2} / T} \quad (18)$$

(For derivation see Appendix B) where i_s represents the electron current at 0 field strength and i represents the current at any field strength E .

By measuring the current at various anode voltages and plotting values of $\log i$ against $V^{1/2}$, a straight line is obtained. If this is extrapolated back to 0 volt, the value of i at 0 field strength may be determined. This equation holds for clean metals but is not valid for thoriated or oxide-coated or other composite filament surfaces. In order to influence the thermionic emission by, say, 10 per cent ($T = 2000$), the field strength required close to the surface of a filament would be 1890V per centimeter. A field of this strength would be produced at the surface of a wire 0.01 cm. in diameter inside of a cylindrical anode 1 cm. in diameter by an applied potential of 43.5 volts. Thus the Schottky effect, although easily measurable, is not of great importance at low voltages.

8. Field Currents.

From quantitative considerations it would be expected that the greater the field strength the more pronounced the effect would be. Eventually a limiting value is

reached at which the work function vanishes and the current increases to a limiting value

$$I = AT^2 \quad (19)$$

This field current is very large compared with the magnitude of thermionic currents at ordinary temperatures, and its temperature coefficient is very small. For tungsten the limiting field is 1.44×10^8 volts per centimeter. At this field strength the current from tungsten at room temperature would be 5.4×10^7 amp. per square centimeter.

9. Initial Velocities.

At zero anode potential, electrons having just sufficient energy to overcome the forces at the surface will escape from the metal with zero initial velocities. Electrons having larger amounts of kinetic energy will not only be able to get away from the surface but will escape with an excess of energy. The result is that these electrons will have appreciable initial velocities and will be able to move against a retarding voltage. The consequences of these initial velocities will be discussed further in Chap. VIII. It is due to the initial velocities of the emitted electrons that small currents are observed in vacuum-tube circuits at zero or very low anode voltages. It is customary, for convenience, to state the velocity of the electrons in terms of the opposing voltage against which they can just travel, instead of expressing it in centimeters per second. Thus an electron which can travel against an opposing field of 1 volt is said to have a velocity or energy of 1 volt. Actually its velocity is determined by the equation

$$\frac{1}{2}mv^2 = Ve$$

The higher the temperature of the cathode the more electrons there will be with any given velocity and the

higher will be the mean energy of the emitted electrons. Thus the mean energy is only 0.052 volt at 300°K., 0.41 volt at 2400 and 0.63 volt at 3655°K. Only one out of 1000 electrons from a cathode at 2400°K. has an initial velocity greater than 1.43 volts.

10. The Schroteffekt (Small-shot Effect).

The passage of the thermionic current in a vacuum tube is not a smooth continuous flow. Owing to the atomic constitution of electricity, the electrons pass from the cathode to the anode as a hail of elementary charges. If the rate of emission of these elementary charges were uniform, they would give rise to small regular variations in the thermionic current and the frequency of these variations would be determined by the number of electrons per second. Stated in another way, the space current in a vacuum tube is lumpy because of the granular nature of electricity.

The emission of electrons, however, does not take place at a uniform rate. In very short consecutive time intervals, there are sometimes more and sometimes fewer charges emitted than the average number as determined over a long time interval. Thus for each small arbitrary time interval there may be considered to exist an alternating component of the discharge current.

The random positive and negative variations from the mean in the number of electrons emitted in successive intervals correspond to the amplitude of this alternating current.

Let $n_{\Delta t}$ be the actual number of electrons escaping in a time interval Δt , and let \bar{n} be the average number of electrons escaping per unit time. Then the average number escaping in time Δt will be $\bar{n}\Delta t$. According to the probability theorem

$$\overline{(n_{\Delta t} - \bar{n}\Delta t)^2} = \bar{n}\Delta t \quad (20)$$

Multiplying by $(e/\Delta t)^2$:

$$\left[\frac{(n_{\Delta t} - \bar{n}\Delta t)^2 e^2}{\Delta t^2} \right] = \bar{n} e \frac{e}{\Delta t} \quad (21)$$

The left-hand side of this equation represents the mean square value of the variations of the short-period average current $i_{\Delta t}$ from the long-period average i_0 . Therefore,

$$i_{\Delta t} = \sqrt{\frac{i_0 e}{\Delta t}} \quad (22)$$

From this equation it can be seen that these deviations increase with the size of the elementary unit of electricity. Thus if electricity were an infinitely fine-grained fluid, the fluctuations would be zero.

This hypothesis is based on the assumption that the electrons are emitted independently of one another and that the emission of any one electron does not affect in any way the emission of the next electron.

The consequence of this Schroteffekt upon radio tubes is of interest, for it is one of the factors which sets a limit to the degree of amplification attainable. These variations in current, when sufficiently amplified, give rise to a noise in the output circuit. The nature of the effect demands that, for it to be a maximum, the emission must be limited by temperature. Ordinarily, however, the emission in amplifiers is limited by space charge which tends to reduce the effect.

If the space current is passed through the inductance and resistance of a resonant circuit, the voltage fluctuations due to the Schroteffekt will set up oscillations in this circuit which may be amplified further by additional stages and finally measured by suitable means. By measuring the magnitude of the Schroteffekt, Hull and Williams have determined the value of e , the electronic charge. Conversely, other experimenters using the

already known value of e have used the phenomenon as a means of studying the basic assumptions underlying the theory.

TABLE I.*—WORK FUNCTIONS AND ATOMIC RADII FOR VARIOUS ELEMENTS

Element	Work function, (ϕ) volts	Atomic radii, centimeters
Calcium . . .	2 24	1.96×10^{-8}
Caesium	1 81	2 37
Molybdenum	4 44	1 36
Nickel . . .	2 77	1 25
Platinum	6 27	1 39
Tantalum . .	4 07	1.41
Thorium	3 35	1.77
Tungsten . .	4.52	1 36
Zirconium .	4 13	1 59

* Values taken from Dushman, *Rev. Mod. Phys.*, **2**, 394, 1930.

TABLE II.*— b_0 FOR VARIOUS ELEMENTS

Element	b_0	I emission, amperes per square centimeter
Calcium.. . . .	35,000	4×10^{-3} (3)
Caesium.....	21,000	
Molybdenum.	51,500	1.6×10^{-3} (2)
Nickel....	32,100	
Platinum	72,500	3×10^{-3} (1)
Tantalum...	47,200	4×10^{-3} (2)
Thorium	38,900	4.3×10^{-3} (1)
Tungsten	52,400	1×10^{-3} (2)
Zirconium	47,900	5.5×10^{-2} (2)

(1) Measured at 1600°K.

(2) Measured at 2000°K

(3) Measured at 1100°K.

* Values taken from Dushman, *Rev. Mod. Phys.*, **2**, 394, 1930.

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CHAPTER II

VARIOUS THERMIONIC EMITTERS INCLUDING THORIUM

11. Emission and Vapor Pressure.

It was shown in Chap. I that substances differ greatly in their thermionic emitting properties. Table II gives values of b_0 and I for various elements, measured, where possible, at the same temperature. From this table it can be seen that substances such as thorium, calcium, barium, strontium or caesium are much better thermionic emitters than substances such as tungsten, molybdenum, tantalum or platinum. In the choice of an electron emitter, however, other considerations than the efficiency of emission alone play a large part. For example, an element such as calcium has a low work function, 3.02 volts, and is a fairly good emitter as compared with many other substances at the same temperature. The vapor pressure of calcium, however, is so high that its evaporation becomes appreciable at relatively low temperatures. The result is that it is not possible to operate a calcium surface at a high enough temperature to obtain large electron currents. A substance such as tungsten on the other hand, although a comparatively poor emitter, can be operated at very high temperatures. Accordingly it can yield high electron currents, although its efficiency in terms of milliamperes of electron current per watt of heating energy may be very low. Fortunately it is sometimes possible to use a combination of a material with low emission but which can operate at high temperatures, and another substance with high emission but a high vapor pressure.

12. Thoriated Tungsten.

The best known instance of such a combination is thoriated tungsten. The melting point of tungsten is 3655°K. , and its work function is 4.52 volts. At a temperature of 2000°K. a tungsten filament can be operated for tens of thousands of hours without appreciable evaporation, but its emission at this temperature is only 10^{-3} amp. per square centimeter. Thorium has a low work function of 3.35 volts and is a very good emitter, but it melts at 2118°K. Fortunately it is possible for tungsten to adsorb strongly a layer of thorium on its surface and hold it there at temperatures far above the point where pure thorium would melt and evaporate rapidly. Such a thoriated filament has the mechanical properties of tungsten, yet as an electron emitter its properties are greatly modified by the thorium. Thus such a filament can be operated at 2000°K. , which is near the melting point of thorium, and yield an electron current of 2.86 amp. per square centimeter, 1000 times as much as pure tungsten. Similar principles are involved in the caesium emission and the oxide-coated filament.

It is common practice to introduce a small percentage of thoria into the tungsten used for incandescent lamp filaments in order to prevent offsetting.* It was found that when suitably treated these filaments gave values of thermionic emission far in excess of that normally to be expected for pure tungsten. This phenomenon was studied in great detail by Langmuir.

13. Activation.

If a thoriated filament is flashed (*i.e.*, heated for a short time) at a temperature of about 2800°K. and the

* Slipping of crystals in the direction at right angles to the length of the filament.

emission is measured immediately afterward, it will correspond very closely to that from a pure-tungsten surface. If the filament is then held at a temperature in the neighborhood of 2100°K ., the emission will gradually increase until it reaches a value about 1000 times that for pure tungsten at the same temperature.

The explanation of this behavior is that at 2800°K . some of the thoria in the wire is reduced to metallic thorium. The metallic thorium diffuses through the wire, mostly along the grain boundaries, to the surface where it evaporates. At temperatures somewhat below 2800°K ., where the rate of evaporation from the surface is not so high, the thorium can accumulate at the surface where it forms a layer one atom deep. This modifies the electron-emitting properties of the wire without altering its mechanical properties.

The monatomic layer of thorium can be formed only under favorable conditions. The filament temperature must be high enough so that the thorium will diffuse to the surface in appreciable quantities, yet not so high that the thorium will all evaporate from the surface. If the filament temperature is too high, the thorium will evaporate from the surface as fast as the process of diffusion brings it there. At very low temperatures the rate of evaporation becomes smaller, but at the same time the rate of diffusion toward the surface becomes still smaller. Furthermore, if the temperature conditions are right, other causes must not be operating to tend to remove the active layer. For example, in an oxidizing atmosphere the thorium will be converted to thoria as fast as it arrives at the surface, while in the presence of inert gases at sufficiently high anode voltages it may be removed from the surface by the sputtering action of positive ions. The optimum condition (for most commercial thoriated filaments) for the formation of a monatomic thorium surface on tungsten is a high vacuum

and a filament temperature between 2000°K. and 2200°K.

14. Fraction of Surface Covered.

The surface condition of a thoriated filament, *i.e.*, its activity, is studied by measuring the electron emission from it. The laws governing the behavior of such filaments are best determined from the activation curves. These are simply the curves showing the change in emission with time under various operating conditions.

Let us first consider the activation curves. Suppose that the filament has been flashed for 1 min. at 2800°K. Let us make all observations at a filament temperature of 1500°K. , because at this temperature all the processes involved are sufficiently slowed down so that no change takes place during the course of a reading. Figure 4 shows an activation curve obtained by operating a filament at 2100°K. and taking readings at 1-min. intervals, the readings all being made at a temperature of 1500°K. The initial reading shows a very low value of emission corresponding to that for a pure-tungsten surface. The curve then rises rapidly and finally approaches a limiting value as the surface becomes completely covered with thorium. The general nature of this curve is the same for different temperatures of activation, and the emission reaches the same limiting value. The emission from a thorium-covered surface is greater than that from tungsten, and this gradually increasing emission indicates an increasingly large proportion of the surface covered with thorium. The activity of the surface must depend upon the fraction of the surface covered. If half of the surface is completely covered with thorium while the other half is clean tungsten, then, of course, the emission will be the arithmetic mean between the value for thorium and the value for tungsten. If, however, the filament surface is half covered with thorium, but the

latter is distributed uniformly over the entire filament, this will no longer be the case. The effect of the thorium in increasing the emission is not due to a specifically high emission from its surface but is due to the fact that the thorium atoms on the surface raise the potential at the

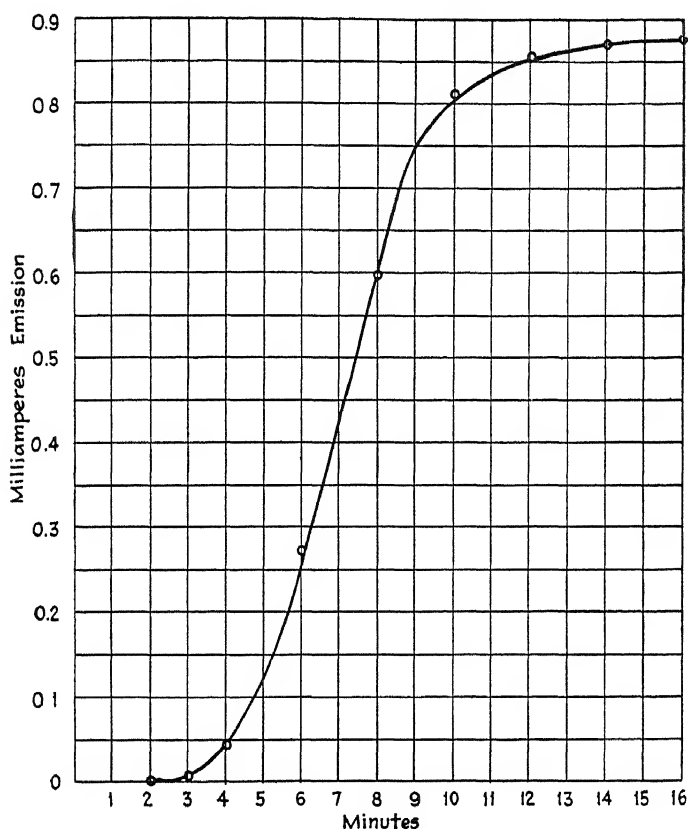


FIG. 4.—Activation curve for thoriated tungsten. Activation temperature 2100°K.; testing temperature 1500°K.; filament area 0.142 sq. cm.

critical surface, thus permitting more electrons to pass this critical region. It has been shown quantitatively from this theory that the logarithm of the emission is a linear function of the fraction of the surface covered, so that

$$\log i_0 = k_1\theta + k_2 \quad (23)$$

The constants can readily be evaluated by setting $\theta = 0$ and $\theta = 1$. When $\theta = 0$,

$$k_2 = \log i_w$$

and when $\theta = 1$,

$$k_1 = \log i_{Th} - \log i_w$$

Accordingly,

$$\theta = \frac{\log i_\theta - \log i_w^*}{\log i_{Th} - \log i_w} \quad (24)$$

where i_w = emission from clean tungsten surface

i_{Th} = emission from a surface completely covered with thorium

i_θ = emission from surface where θ equals fraction covered.

Thus, if the initial and final values of emission are known, it is possible to calculate the fraction of surface covered corresponding to any degree of activation.

If the activation curves are plotted on semilogarithmic paper, as shown in Fig. 5, the ordinates will be proportional to values of θ . These experimental curves can all be represented quite accurately by an exponential formula of the type

$$\log(1 - \theta) = -kt \text{ or } \theta = 1 - e^{-kt} \quad (25)$$

where θ according to 1 is proportional to $\log i$. By differentiation

$$\frac{d\theta}{dt} = k(1 - \theta) \quad (26)$$

This equation expresses the fact that the filament surface is becoming covered with thorium at a rate proportional to the amount of surface left uncovered at any time. When the filament becomes nearly covered (θ

$$^* \theta = \frac{b_\theta - b_w}{b_{Th} - b_w}.$$

nearly 1), a thorium atom may arrive at the surface at a point just under a thorium atom which was already

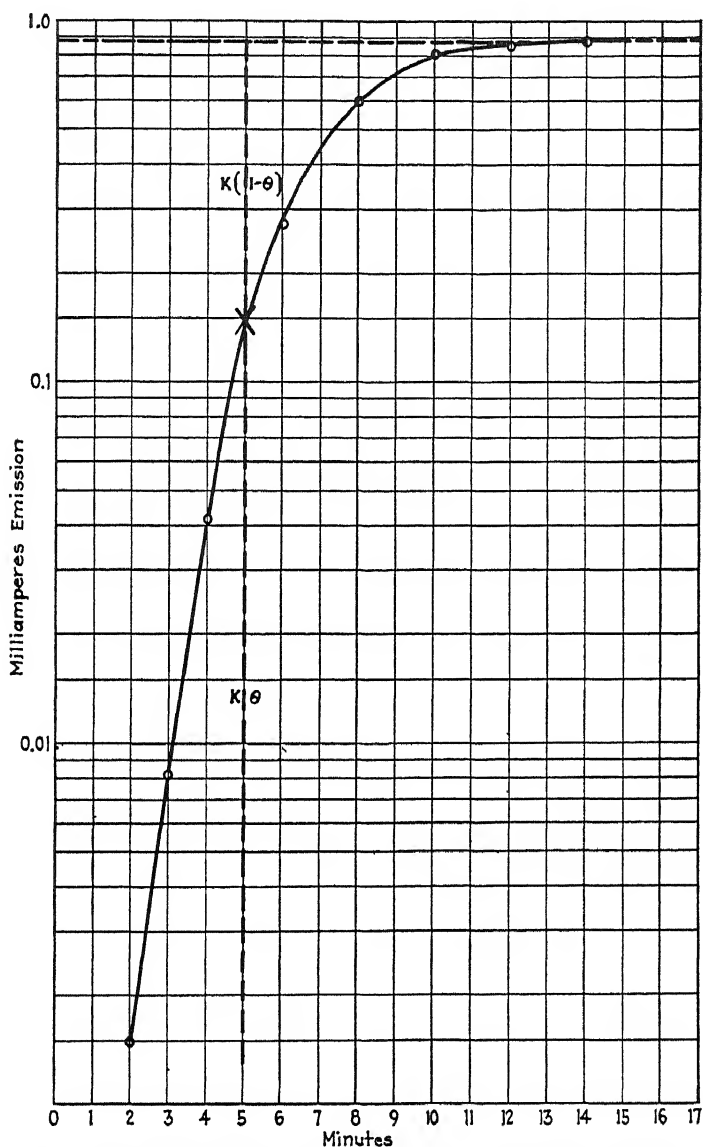


FIG. 5.—Semilogarithmic plot of the activation curve shown in Fig. 4.

there. Since the rate of evaporation of thorium from thorium is much greater than for thorium from tungsten, the surface atom will evaporate because the forces hold-

ing it to the surface are decreased. A thorium atom arriving at the surface then increases the fraction covered only if it arrives at a place not previously covered by thorium; *i.e.*, θ must increase at a rate proportional to $1 - \theta$.*

15. Diffusion.

The rate at which thorium arrives at the surface is proportional to the concentration gradient of thorium in the wire and to the rate of diffusion. When the proportionality constant of Eq. (26) is replaced by these values, it becomes

$$N_0 \frac{d\theta}{dt} = DG(1 - \theta) \quad (27)$$

where D = diffusion constant in atoms per square centimeter per second per unit gradient

G = concentration gradient

N_0 = number of atoms per square centimeter on a completely covered surface.

16. Evaporation.

This equation applies only at comparatively low temperatures where the rate of evaporation from the surface is negligibly small. At higher temperatures, where the rate of evaporation from the surface becomes appreciable, an equilibrium is reached between the rate of evaporation from the surface and the rate of arrival at the surface. Accordingly Eq. (27) becomes

$$N_0 \frac{d\theta}{dt} = DG(1 - \theta) - E \quad (28)$$

where E = rate of evaporation in atoms per square centimeter per second.

* Since this was written a different viewpoint has been presented in a paper by W. H. Brattain and J. A. Becker; Thermionic and Adsorption Characteristics of Thorium on Tungsten, *Phys. Rev.*, **43**, 428, 1933.

At high temperatures where E is large compared with DG , the filament surface can never become completely covered with thorium, *i.e.*, θ is always less than 1 and the filament never becomes completely activated. In practice this holds true for temperatures of about 2300°K. or more.

17. Equilibrium Conditions.

Practically all of the observed facts of thoriated emission can be explained in terms of the theory just outlined. By a series of measurements made under varying conditions the following values have been determined for E and D :

$$\log_{10} E = 31.434 - \frac{44,500}{T} \quad (29)$$

$$\log_{10} D = 0.044 - \frac{20,540}{T} \quad (30)$$

From these two equations it can be seen that the evaporation increases much more rapidly with temperature than the rate of diffusion.

The behavior of thoriated filaments can best be summarized by stating the three most important processes which are taking place during operation:

1. Reduction of thoria to metallic thorium.
2. Diffusion of thorium toward the surface.
3. Evaporation of thorium from the surface.

The relative importance of these three processes depends upon the temperature of the filament. At temperatures of 2800°K. or above, thoria is rapidly being reduced and diffuses toward the surface. The rate of evaporation is so rapid, however, that the surface cannot become covered, and the filament behaves essentially as though it were pure tungsten.

At temperatures below 2800°K. the rate of reduction of thoria is low. The rate of evaporation is low enough so that the surface may be maintained partly covered with thorium. At temperatures below 2300°K. the

diffusion to the surface and the rate of evaporation both decrease, but the latter more rapidly than the former so that the surface may become completely covered with thorium and the filament emission will be the high-value characteristic of thorium.

For any filament temperature, then, there is an equilibrium condition of the surface, a balance between the rate of supply and the rate of loss of the thorium. This equilibrium may be approached from either side. For example, suppose that a filament is completely activated, *i.e.*, the surface is entirely coated with thorium. If the temperature of the filament is raised to 2400°K ., it will deactivate until only a fraction of the surface remains covered. On the other hand, if we start with the filament in a deactivated condition and operate it at 2400°K ., it will activate until the same fraction of the surface is covered as in the previous case.

To some extent this condition will be modified by the history of the filament. For example, a filament which has never been flashed at 2800°K . will not show any activation phenomena because no thorium has been produced in the body of the wire, although in some cases a small amount of thorium may be present as the result of the wire-drawing process. A wire which has been flashed for only a few seconds will not contain the same reserve supply of thorium as one which has been flashed for perhaps a minute so that the amount of thorium diffusing to the surface in a given time will be less and may not be sufficient to replace the loss by evaporation. Similarly, if a filament has been operated for a long time so that the reserve of thorium is used up, diffusion will not be able to make up for evaporation losses so that the activity of the surface will be low.

18. Emission Life of Thoriated Filaments.

This exhaustion of the reserve supply of thorium is one of the common causes of the termination of the life

of thoriated-filament vacuum tubes. The filament can be restored to its initial condition by flashing again for a brief period at 2800°K . and then operating at a temperature of about 2200°K . to give this renewed supply of thorium an opportunity to cover the surface. This process may be repeated many times as the quantity of thorium reduced is only a very small fraction of the total quantity of thoria present.

The emission life of a thoriated filament depends upon the reserve of thorium available and on the rate at which it is used up. The reserve is merely the concentration originally in the wire. The temperature at which the wire is operated determines the rate at which it is used up by diffusion to, and evaporation from, the surface.

Thoriated filaments in electron tubes usually contain not more than 1.5 per cent by weight of thorium. A larger quantity than this makes the drawing of the wire difficult, while a smaller quantity may not yield a sufficient supply of thorium. Different ways of treating the wire in the processing also affect the ease of reduction of the thoria to thorium. Another factor which must be taken into consideration is the grain size of the wire. Most of the diffusion of thorium is now believed to take place along the grain boundaries rather than through the metal itself. Accordingly it is necessary to have a wire constituted of fairly small grains in order to furnish a sufficient number of paths along which diffusion can take place. Large-size grains would cut down the number of paths and so decrease the rate of arrival of thorium at the surface while not affecting the evaporation from the surface.

19. Effects of Gases.

In the presence of gas the equilibrium conditions are altered. Inert gases such as the rare gases argon, helium and neon may remove atoms of thorium from the

surface by sputtering, while a chemically active gas such as oxygen, water vapor or carbon dioxide will rapidly oxidize the surface film.

The effect of oxidation is completely to alter the electron-emitting properties of the surface. A tungsten filament which is completely covered with oxygen has a value of $A = 5 \times 10^{11}$ and $b_0 = 107,000$; *i.e.*, the work function for an oxidized surface is very much higher than for a clean surface, so that the emission from an oxidized tungsten surface is one-millionth that of a clean surface.

20. Relation between A and θ .

The constant A of the Richardson equation was given in Chap. I as 60.2 for all pure metals. For composite surfaces, however, such as thoriated tungsten and oxide-coated or caesiated filaments, A is no longer a constant but depends upon the condition of the surface, *i.e.*, on the value of θ , the fraction of the surface covered. This relation is shown graphically in Fig. 6. This curve may be represented by the empirical formula

$$A_\theta = [7^\theta + 60^{(1-\theta)} - 1]A_0 \quad (31)$$

where $A_0 = 1$ amp. per square centimeter.

Thoriated tungsten has been discussed in great detail because of its importance in the vacuum-tube art and because its behavior is typical of a great many other electron emitters. It has been possible to study electron emission from pure substances only in the case of the few metallic elements which have high melting points and low vapor pressures and can readily be made into wires. Other substances must be studied by coating them upon wires or incorporating them in the wires, as has been done with thoria. In this fashion, elements such as cerium, zirconium, lanthanum, yttrium, uranium,

calcium, magnesium, strontium, barium and others have been investigated. The principles involved are the same as those just discussed, but the quantitative relationships depend upon the properties of the elements in question. The metallurgy of such combinations is often very difficult and imposes limits upon the investigation.

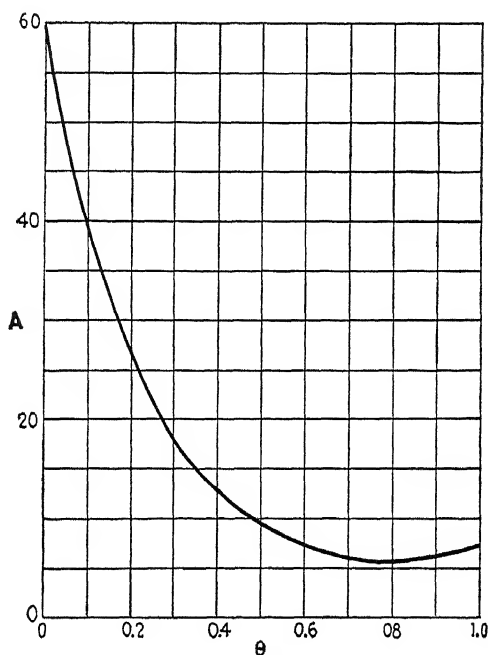


FIG. 6.—Relation between A and θ for thoriated tungsten. (K. H. Kingdon, *Phys. Rev.*, **24**, 511, 1924.)

21. Carbonization.

A very interesting process which greatly improves the performance of thoriated filaments is carbonization. If a tungsten filament is operated at a temperature above 1600°K . in the vapor of naphthalene (C_{10}H_8), every molecule of naphthalene which strikes the hot surface of the filament decomposes into carbon and hydrogen. The carbon deposited on the surface diffuses into the tungsten forming the compound, tungsten carbide. This behavior is not limited to naphthalene but takes

place with any convenient hydrocarbon such as alcohol, benzol, benzene, toluene, anthracene, methane, acetylene or illuminating gas.

At very low pressures and high filament temperatures the rate of formation of carbide is limited only by the rate at which molecules strike the surface. The rate of diffusion into the filament is more than able to keep pace with the number of atoms of carbon formed on the surface. At high pressures of the hydrocarbon vapor and low filament temperatures the process is limited by the rate of diffusion; *i.e.*, carbon is formed faster than the wire can take it up and there is a tendency to form a shell of carbon on the surface of the wire.

The electrical resistance of tungsten carbide is higher than that of tungsten. This provides a very convenient indicator for controlling the carbonization process. As the carbon diffuses into the wire, forming carbide, it forms a shell which can readily be seen under the microscope, as shown in Fig. 7. The filament thus consists of a core of tungsten surrounded by a concentric shell of tungsten carbide (W_2C). Since the specific resistances of these two substances are known, it is a simple matter to compute the resistance of the filament corresponding to any degree of carbonization. The relation between the degree of carbonization and conductivity of the filament is shown in Fig. 8. The initial conductivity is taken as 100 per cent. As the filament is converted to tungsten carbide, the conductivity decreases linearly until it reaches 6 per cent of its initial value. This has been found experimentally to correspond to a carbon content of 3.16 per cent by weight, which is the amount of carbon required to convert the entire filament to W_2C . If the carbonizing process is continued beyond this point, the conductivity increases again because the filament is being converted to another carbide of tungsten, WC , which has a higher conductivity than W_2C .



FIG. 7.—Longitudinal section of carbonized tungsten filament showing carbide shell and tungsten core.

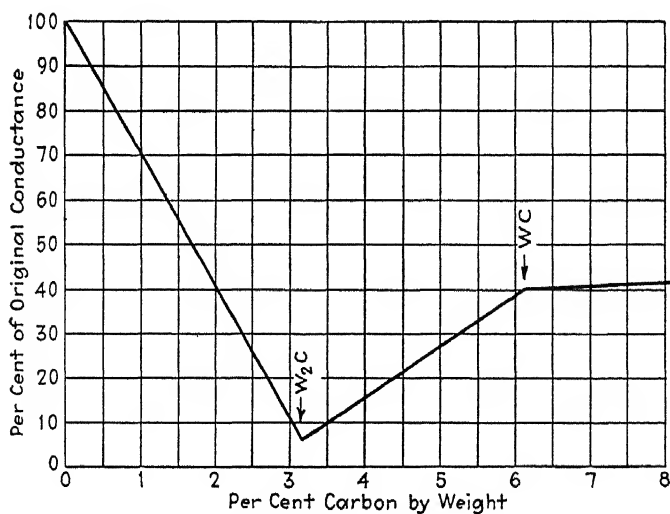


FIG. 8.—Relation between conductivity and carbon content of carbonized tungsten filament. (M. R. Andrews, *J. Phys. Chem.*, **27**, 275, 1923.)

This stage of the process is quite similar to the first. An outer shell or ring of this higher carbide is formed which gradually works in toward the center as the carbon diffuses until the entire filament is converted to WC. At this point the conductivity is 40 per cent of its initial value and the carbon content is 6.12 per cent by weight. If the process is continued, there is only a very slight increase in conductivity which is due to the solution of carbon in the carbide.

This process can be reversed and the filament decarbonized by pumping out the hydrocarbon vapor and heating the filament to 2400°K . or higher. The carbide decomposes and the carbon is vaporized off the filament surface restoring it to its original condition.

Carbonization has a remarkable effect on the operation of thoriated filaments. It has been found that the rate of evaporation of thorium from a carbonized filament at a temperature of 2200°K . is only about one-sixth of that for a tungsten surface at the same temperature. Carbonized filaments can therefore be operated at higher temperatures than uncarbonized filaments without deactivating the surface by evaporation of thorium. Since the operating temperature can be raised, the accompanying increase in the rate of diffusion results in an increased amount of thorium being brought to the surface, while the evaporation at the higher temperature is no higher than for a plain filament at the same temperature. The result is that carbonized filaments can be operated under adverse conditions, such as an oxidizing atmosphere or positive-ion bombardment, where uncarbonized filaments would fail to give thoriated emission.

Tungsten carbide is brittle, so that in order not to weaken the filaments excessively it is customary not to carbonize beyond the point where the conductivity is 80 per cent of its initial value.

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CHAPTER III

OXIDE-COATED CATHODES

22. Preparation of Cathodes.

One of the first and most widely used types of thermionic emitters was the oxide-coated or Wehnelt cathode, so called after its discoverer. In 1904, in the course of some measurements of cathode drop in gaseous discharges, Wehnelt found that the oxides of barium, strontium and calcium, coated upon platinum, were particularly effective in lowering the cathode drop, *i.e.*, they were good electron emitters.

Although the oxide-coated cathode differs greatly from the thoriated filament, it resembles it in that the emitting material is a coating upon a core of some other material. Various methods of making oxide-coated cathodes have been devised and are at present used commercially. They are all similar in that the end result is a coating composed primarily of oxides of barium and strontium adhering to a metal core.

In one of the earliest commercial processes the carbonates of barium and strontium are mixed in approximately equal proportions with a carrier such as resin or paraffin. This is then applied to the hot wire in air. The carrier is then burned off by raising the temperature of the wire, and successive coats are applied in a similar manner until the desired thickness is attained.

Other methods involve passing the wire through a paste containing a mixture of the carbonates, which is then baked on to the surface at a temperature well below red heat, usually in an atmosphere of carbon

dioxide. This paste may be a suspension of the salts either in water or in an organic binder. The binder is burned off in the process of activating the filament.

Another method consists in dipping the filament into an aqueous solution containing about 3 per cent of barium nitrate and then evaporating the water by heating in an atmosphere of carbon dioxide; then dipping into a strontium nitrate solution and heating in carbon dioxide and repeating the process through as many as 40 cycles or sometimes even more.

Another process makes use of barium azide (BaN_6).^{*} A few drops of a solution of the azide is placed upon the inside of the anode of the vacuum tube and evaporated to dryness at 100°C . Barium azide decomposes above 130°C . into metallic barium and nitrogen. During the exhaust process this temperature is exceeded and decomposition takes place. The nitrogen is pumped out, leaving a deposit of pure barium on the inside of the anode. When the latter is heated by high-frequency induction the barium vaporizes, and some of it condenses on the filament. In order to insure the barium adhering to the filament and giving satisfactory emission life, the surface of the filament must be oxidized. The filaments used in this process are for the most part either tungsten or platinum with an electrodeposited layer of copper.

The difference in emission between barium and strontium is slight, but it has been found that coatings containing strontium adhere better to the filament surface than those of barium alone and seem to have a longer life. Accordingly a mixture of the two is used, usually in the proportion of 3 parts of barium to 2 parts of strontium. It is customary in the literature on this subject to use the word "barium" where both barium and strontium are meant.

^{*} Barium azide is an unstable compound and under some conditions may be a very dangerous explosive.

A wide variety of core materials are used. Platinum, usually in the form of platinum-iridium or platinum-nickel alloy; nickel; tungsten and tungsten electroplated with copper; and an alloy of nickel, cobalt, iron and titanium known as *konel*. The effect of the core material will be discussed later.

23. Activation.

A freshly prepared oxide-coated cathode does not show any appreciable electron emission. It must first be activated. The activation process assumes different forms, depending upon the coating process which has been used. In general, it consists in heating the filament for several minutes at a temperature from 1000°K. to 1500°K. , or well above the operating range. This is followed by a period of operation at a lower temperature for a longer time with anode voltage applied. During this treatment the filament emission increases rapidly to its maximum value. The exact procedure varies greatly for the different types of coatings.

The phenomena underlying the activation process in the case of coated filaments are very different from those in thoriated filaments. Diffusion to the surface probably is an important factor, but it is not determined by temperature alone as in the case of thoriated filaments. The fact that the activation is dependent upon anode voltage shows that it is partly electrolytic in nature. At any given anode voltage and filament temperature the emission from a coated filament will reach an equilibrium value. On raising the anode voltage (keeping the filament temperature constant) the emission will gradually increase to a new value. On further increasing the voltage a further increase in emission will result. A decrease in voltage will result in a decrease in emission although not necessarily to the same value as observed before. This effect shows an appreciable time lag, and

several minutes may be required to establish equilibrium. The magnitude of this effect varies for different types of coated filaments, but the general trend is the same for all.

In some processes the application of anode voltage during the activation is essential, and in the earlier processes it was even necessary for a glow discharge to take place before the filament could be activated. In other processes such as those where a konel wire core is used, the activation appears to be purely thermal.

24. Measurements.

Comparison of the efficiency of different types of oxide-coated cathodes is rather difficult owing to the difficulty in determining the constants in the emission equation. For pure metals these are relatively easy to determine, but in the case of oxide-coated filaments the temperature cannot be accurately measured owing to lack of knowledge of the thermal emissivity of the surface. This depends not only upon the chemical nature of the surface but also upon its physical state, which is influenced by the process which has been used in preparing it. The simplest comparison, therefore, is on an energy basis, *i.e.*, in terms of amperes of electron current per watt input of heating energy. A very convenient form of cross-section paper has been devised by Davisson for representing data in this form. This paper, called power emission paper, is shown in Fig. 9. If values of emission per square centimeter are plotted against watts per square centimeter (energy input to the cathode) on this paper, a straight line will result for any substance whose thermionic emission follows Richardson's equation. Values for pure tungsten, thoriated tungsten and oxide-coated nickel are shown in the figure. For practical purposes this paper is very convenient, as it is not necessary to know temperatures or radiation constants in making use of it.

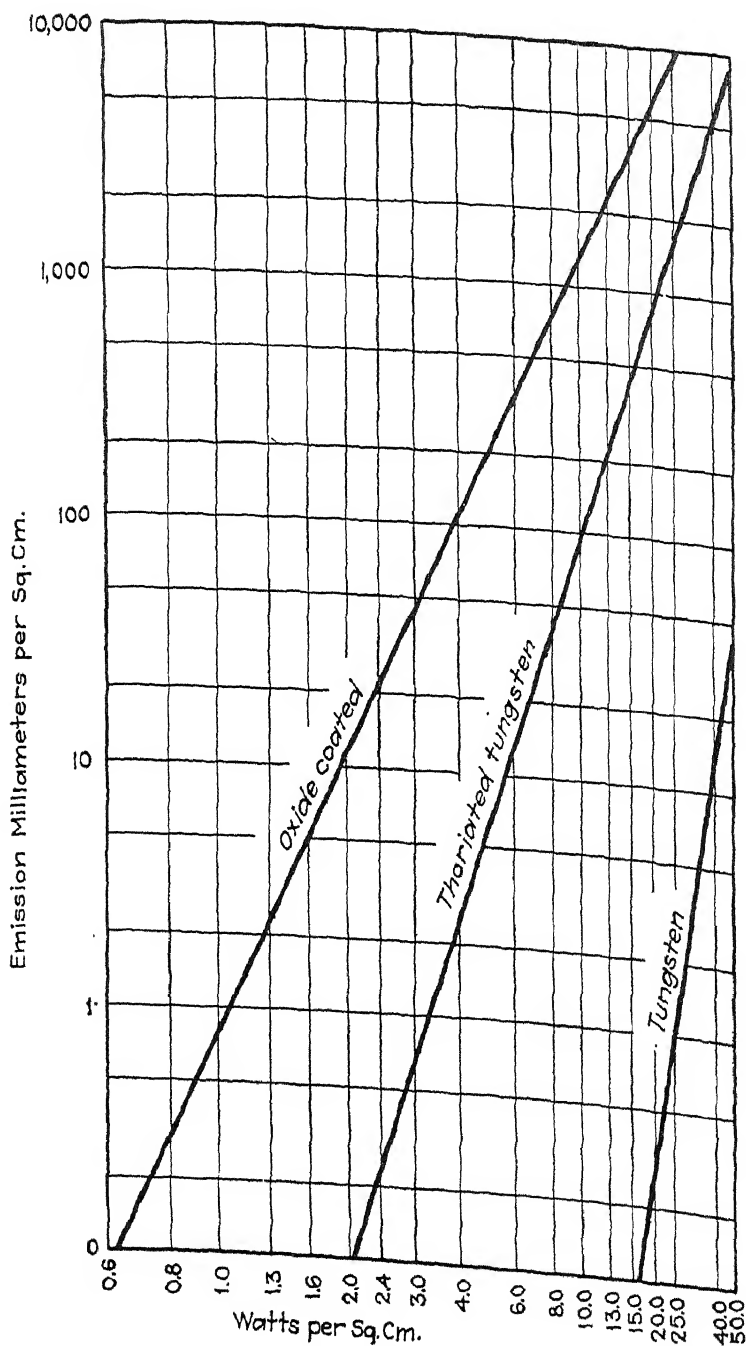


FIG. 9.—Emission from various substances plotted on power emission paper.
(R. W. King, *Bell System Tech. J.*, 2, 31, 1923.)

One feature of the behavior of coated filaments which is particularly noticeable is the lack of saturation of the emission with increasing anode voltage. This is probably due in part to the electrolytic nature of some of the phenomena involved and in part to the fact that the cathode surfaces are rough so there are many crevices from which the electrons do not escape at low voltages, but from which they are pulled out in increasing numbers as the voltage is raised.

25. Theories of Behavior.

The theory of the behavior of coated filaments is in a very unsatisfactory state. Different observers obtain radically different results. This is partly because of the variety of types of cathodes which have been used in the investigations. Furthermore, it is very difficult to get reproducible results, even with any one type of cathode. Factors, such as the fineness of the powders used for the coating, and the method of applying it, exert a very great effect which, as yet, has not been completely determined. According to one view, the emission is due to a monatomic film of barium on the surface of the filament, much as in the case of thoriated filaments. According to another view, the emission is due to a highly emitting layer at the interface between the core and the coating, electrons finding their way out through the porous coating. There is good evidence to support both of these theories.

There is considerable evidence to show that electrolysis within the coating is responsible for many of the phenomena which are observed. This is not a simple electrolysis of the coating, however, which would merely result in an accumulation of barium near the surface of the core. The barium probably takes part in the process repeatedly, moving toward the core in the form of barium ions which lose their charge and diffuse back as atoms.

The fact that coated filaments cease to be active as electron emitters while there is still a large amount of coating left is one of the many difficulties which remain to be explained. This indicates that the life is terminated by some change in physical structure rather than by exhaustion of the barium supply.

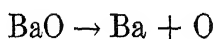
The crystal structure of the filament certainly must have an important bearing on its behavior, since diffusion is one of the important phenomena in coated filaments. Diffusion takes place most readily along grain boundaries. Growth of grains, with consequent reduction of the number of boundaries and paths along which diffusion can take place, has been suggested as one of the causes of the loss of emission of coated filaments. The conditions, however, are not simple as in the case of thoriated filaments, and the evidence in favor of this theory is not entirely conclusive.

Probably all of the processes mentioned play some part in explaining the behavior of coated filaments, but the exact extent of each one is as yet unknown.

Any theory to account for the behavior of oxide-coated cathodes must explain the formation of metallic barium. It has been shown by several experimenters that metallic barium evaporates from the surface of oxide-coated cathodes during their operation, and, furthermore, it has been shown that the characteristic emission is obtained when barium from another source is evaporated on to the surface of a filament. The three possibilities for the production of metallic barium are:

1. Thermal decomposition of the oxide
2. Chemical reduction
3. Electrolytic reduction.

Calculations based on thermodynamic considerations indicate that it is highly improbable that barium oxide would be dissociated to a sufficient extent by heat alone in accordance with the equation



Chemical reduction probably takes place, due to a reaction between the core material and the coating. This is especially true of the konel wire core where the titanium is the active reducing agent. Reducing material, such as nickel powder, is sometimes added to the coating mix. Carbon particles from the organic binder also probably assist in the reduction.

Electrolytic action almost certainly takes place. One very convincing piece of evidence of this is the liberation of oxygen when an electron current is drawn from a coated cathode by the application of anode voltage.

The fact that metallic barium is necessary for an active surface is shown by the fact that, when metallic barium from another source is deposited upon a filament surface, the surface becomes active. A very slight trace of oxygen is sufficient to "poison" the emission from a coated cathode. This is additional evidence in favor of the view that the activity is due to the presence of metallic barium as it is difficult to see how oxygen could be harmful to a barium oxide surface.

One effect of the anode voltage in activating coated cathodes is ion bombardment. Electrons from the cathode in passing to the anode ionize some of the gas in the space between the electrodes. The positive ions formed are driven toward the cathode. This positive-ion bombardment of the cathode surface has a marked effect in activating the filament. This is probably due to a dissociation or reduction of the oxide by the ions.

The core material has two functions. One of these is simply to act as a carrier for the active coating. The only requirement here is that the core must not evaporate and must have sufficient mechanical strength at the temperature at which the cathode is operated. Several metals are able to meet this requirement. The other function, which is less clearly understood, is that of a reducing agent for the coating. Several observers found

that the material of the core had no effect on the emission from the filament. The later measurements from konel alloy, however, indicate that the core may, under some conditions, profoundly affect the emission. For example, Lowry finds that the emission from coated konel wire at 775°C. is as high as from coated platinum at 950°C.

26. Work Function.

The most accurate determination of the work function of coated filaments is that of Davisson who gives $\phi = 1$ volt. This corresponds to $b_0 = 11,600$. The emission for this surface was 91.8 amp. per square centimeter at 1000°K.

27. Indirectly Heated Cathodes.

Oxide-coated cathodes are particularly well suited for forms of cathodes other than filaments. Where it is desired to operate the tube from an alternating-current supply, it is necessary to separate the cathode from the heater element and to heat the cathode indirectly. When this is done, the potential of the cathode is uniform over its surface and for this reason such cathodes are sometimes called unipotential cathodes. Two types of indirectly heated cathodes have been used.

In the first type, shown in Fig. 10, a tungsten filament is threaded through a small hole in an insulator of refractory material. Over this insulator is a tightly fitting sleeve of nickel which is coated with the oxides. The tungsten filament heats the oxides indirectly by conduction through the refractory. This is a very effective means of heating a large cathode surface. For example, a receiving tube having an indirectly heated cathode 2.3 cm. long and 0.204 cm. in diameter requires an energy input of 4.375 watts in order to operate at the proper temperature. This energy is obtained by

passing a current of 1.75 amp. at 2.5 volts through a 6-mil tungsten filament 5 cm. long. In order to radiate this same amount of energy from a solid-nickel filament of the same dimensions as the cathode, a current of 60 amp. would be required. The high specific resistance

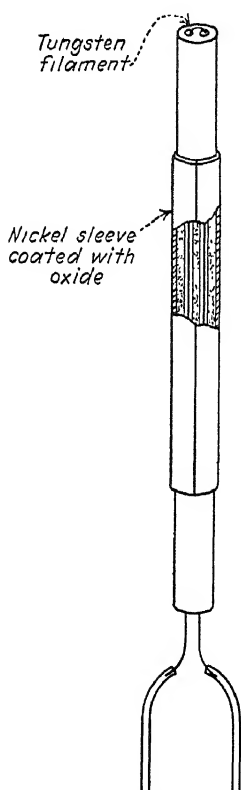


FIG. 10.—Indirectly heated oxide-coated cathode.

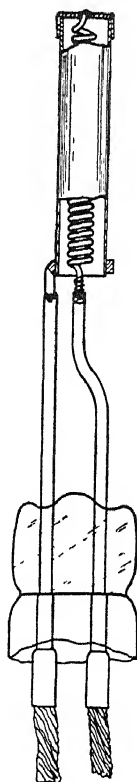


FIG. 11.—Radiator-type cathode.

of the hot tungsten makes it possible to obtain this energy at reasonable values of current and voltage.

The requirements for a refractory for this purpose are high heat conductivity, high electrical resistance and, of course, sufficient mechanical strength. The refractory must also have a high melting point and must not react with the filament material at any temperature within the operating range. Magnesium oxide is very com-

monly used as it has a very high melting point, 2800°C. Aluminum oxide and beryllium oxide have lower melting points than magnesium oxide, but up to their melting points they do not react with the hot filament.

Where larger sizes of cathode are used, the indirect heating is attained by radiation alone. This type of cathode is shown in Fig. 11. A helical tungsten filament is placed inside of a nickel cylinder which is coated on the outside with the emitting material. The principle involved is the same. In these large cathodes, however, it is possible to make the component parts sufficiently rigid so that the support afforded by the insulator is not necessary and the heating takes place by radiation alone. This type of cathode is discussed more fully in Chap. VI on Determination of Temperature.

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CHAPTER IV

THERMIONIC EMISSION FROM CAESIUM

28. Vapor Pressure of Caesium.

Perhaps the most interesting thermionic emitter of all is the caesiated cathode. This type of cathode consists of a layer of the alkali metal, caesium, deposited on a surface of tungsten. The difference in the physical properties of these two elements is even more striking than in the case of thorium and tungsten. The melting point of tungsten is the highest of any of the known elements, $3370^{\circ}\text{C}.$, while that of caesium is $26.4^{\circ}\text{C}.$, only a few degrees above room temperature. The caesium is not incorporated in the wire as in the case of thorium, or applied as a coating as in the case of barium, but is deposited from the vapor.

The vapor pressure of caesium is relatively high for a metal, being 3×10^{-3} barye at $30^{\circ}\text{C}.$ * If a little caesium is placed in a vacuum tube, it will evaporate until the bulb is filled with saturated vapor. The atoms of the vapor, which are in constant random motion, are continually bombarding every surface in the bulb. At the vapor pressure corresponding to $30^{\circ}\text{C}.$, 4×10^{14} atoms strike a unit area of surface per second. Accordingly the surface of a filament in a bulb containing caesium vapor is continually being struck by caesium atoms. These condense on the surface and after a short time reevaporate. The filament will become coated with a monatomic layer in less than three seconds. At low filament temperatures it will remain completely coated. At higher temperatures the caesium will reevaporate, but, since atoms of caesium from the vapor in the bulb

* 1 barye = 1 dyne per sq. cm. = approximately 10^{-6} atm.

are continually condensing on the filament surface, the fraction of the surface covered at any instant will depend upon the relative rate of evaporation from the surface and the number of atoms striking the surface in a given

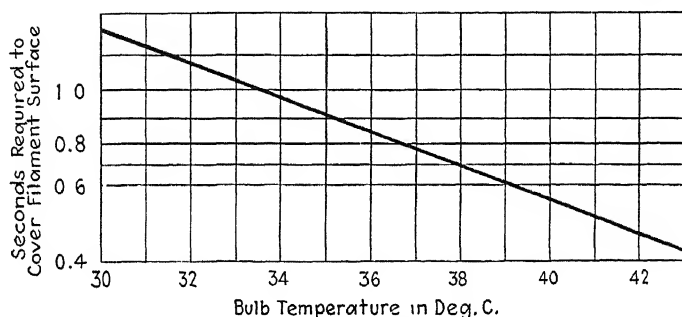


FIG. 12.—Time required to coat a filament with a monatomic layer of caesium at various bulb temperatures.

time. The former depends upon filament temperature, the latter upon vapor pressure, which, in turn, depends upon the temperature of the bulb.

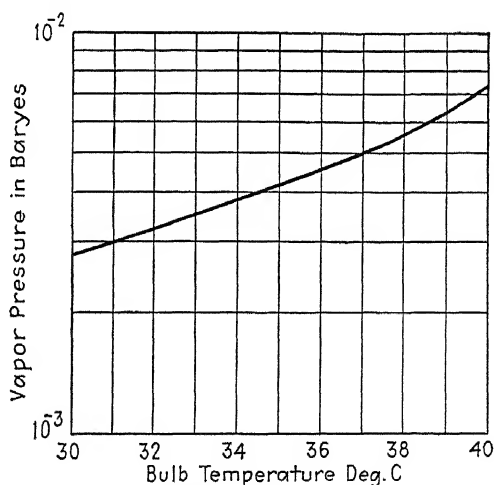


FIG. 13.—Vapor pressure of caesium at various temperatures.

The number of atoms of any gas which strike upon a unit area per second is given by

$$n = \frac{p}{\sqrt{2\pi mkT}} = \frac{2.31 \times 10^{18} p}{\sqrt{T}} \text{ (Atoms per square centimeter per second in the case of caesium)} \quad (32)$$

where m = mass of a molecule

k = Boltzmann constant (1.37×10^{-16} erg per degree)

T = temperature in degrees absolute

p = pressure in baryes.

The relation between the vapor pressure of caesium and the temperature is

$$\log_{10} p = 10.65 - \frac{3992}{T} \quad (33)$$

The time required to coat completely a unit area of filament surface, then, depends upon the bulb temperature in the manner shown in Fig. 12.

Figure 13 shows vapor pressure as a function of bulb temperature.

29. Work Function under Various Operating Conditions.

The effect of a film of caesium upon a tungsten surface is to lower the work function of the surface by an amount which is a function of the fraction of the surface covered. When a caesium atom is adsorbed on the surface of the tungsten, the tungsten and the caesium compete for the valence electron of the caesium. Since the work function of the tungsten is 4.52 volts, while the ionizing potential of the caesium is only 3.88 volts, it is easier to separate the electron from the caesium than from the tungsten; *i.e.*, the tungsten robs the caesium of its electron and the caesium remains on the surface as a positive ion. The effect of an adsorbed layer of positive caesium ions on the surface of the tungsten is to produce a field which assists electrons in escaping from the surface, or, in other words, to lower the work function of the surface.

The work function for a tungsten surface fully covered with caesium is 0.695 volt, corresponding to $b_0 = 8300$. As long as conditions are such that the filament surface

remains fully covered, the relation between emission and temperature follows Richardson's equation. As the filament temperature is raised, a point is finally reached

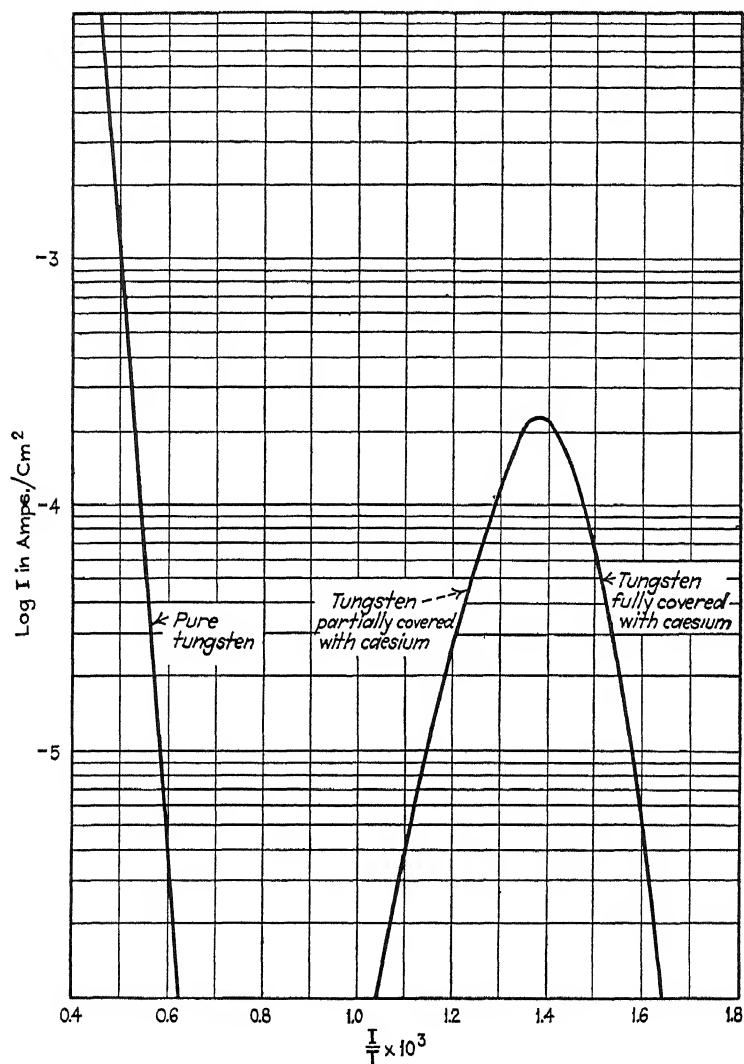


FIG. 14.—Thermionic emission from caesium on tungsten at a bulb temperature of 40° C. (Langmuir and Kingdon, *Proc. Roy. Soc., A* **107**, 75, 1925.)

where the caesium ions begin to evaporate and the filament can no longer remain fully covered. As the temperature is raised still higher, a smaller and smaller fraction of the surface is covered with caesium. This

results in an increase of the work function, and the emission decreases accordingly. In Fig. 14 the portion of the curve to the right of the maximum represents the

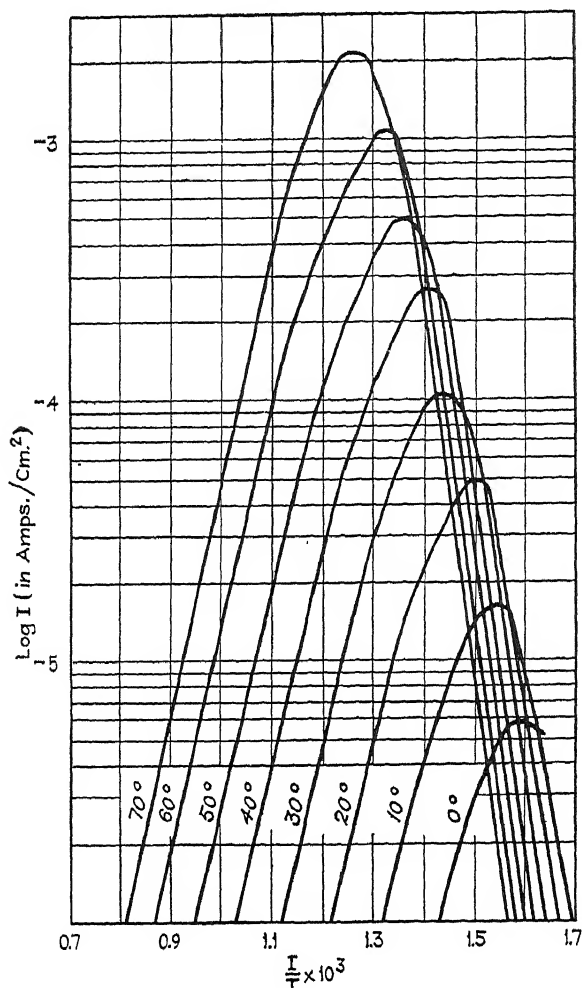


FIG. 15.—Thermionic emission from caesium on tungsten at various bulb temperatures, *i.e.*, at various vapor pressures. (*Langmuir and Kingdon, Proc. Roy. Soc., A 107, 75, 1925.*)

region where the surface is fully covered, and the emission follows Richardson's equation. The portion to the left of the maximum represents the region where the surface is only partially covered, and the emission is falling off with increasing temperature until it reaches a minimum

at the point where no caesium remains on the filament. Here the emission corresponds to that from pure tungsten. As the temperature is raised beyond this point, the emission again follows Richardson's equation with the constants for pure tungsten.

30. Effect of Bulb Temperature.

If the vapor pressure of the caesium is increased by raising the temperature of the bulb, the number of atoms of caesium striking the filament surface in a given time will be increased. This means that the filament can remain fully coated at a higher filament temperature. Accordingly the entire curve of Fig. 14 shifts to the left with increasing bulb temperatures. Figure 15 shows a family of such curves corresponding to different bulb temperatures.

31. Oxygen as a Binder.

The forces holding the caesium to the surface can be greatly increased by the use of a suitable glue or binder. Oxygen serves this purpose admirably. If the filament is first coated with a monatomic film of oxygen, the caesium adheres much more strongly to the oxygen surface than to clean tungsten. The result is that, although the phenomena are qualitatively the same as before, the filament can be raised to a much higher temperature without distilling off the caesium. Thus higher values of electron current can be obtained.

32. Quantitative Aspects.

The maximum emission for caesium on tungsten at a bulb temperature of 30°C. occurs at a filament temperature of about 700°K. and is equal to 10^{-4} amp. per square centimeter. For the case of caesium on *oxygen* on tungsten, at the same bulb temperature, the maximum

occurs at a filament temperature of 1000°K. and is equal to 0.35 amp. per square centimeter. (At the same filament temperature the emission from thoriated tungsten would be 1.73×10^{-7} amp. per square centimeter.) Thus it can readily be seen that a caesiated filament is an extremely good electron emitter.

The oxygen coating is applied by flashing the filament in a low pressure of oxygen, or by admitting oxygen and allowing the cold filament to adsorb a monatomic layer. The excess is then pumped out and the caesium is introduced. If the oxidized filament is not heated above 1800°K. , the caesium surface will be reformed again at lower temperatures and the curve of Fig. 14 can be repeated at will. Above 1800°K. , however, the oxide layer is distilled off and the filament reverts to the caesium on tungsten condition. Once the oxide layer has been distilled off, it cannot be renewed again.

The emission from caesium can be represented by the equation

$$I = \alpha p^{\gamma} \epsilon^{-\beta/T} \quad (34)$$

where α , β and γ have the values given in Table III. For the region over which Richardson's equation is valid

$$A = 0.001, \quad b_0 = 8300, \quad \phi = 0.696.$$

33. Method of Measuring Vapor Pressure.

At temperatures above 1200°K. caesium cannot remain on the surface of the filament, so that the surface remains a clean tungsten one. Under these conditions every atom of caesium which strikes the filament surface is converted into a positive ion; or, in view of the phenomena just presented, the ions are no longer held on the surface but reevaporate. Accordingly, if another electrode is placed in the bulb and made negative with respect to the filament, a positive-ion current will flow

to this collector from the filament. Since every atom which strikes the filament is ionized, this current will be independent of filament temperature. It will also be independent of collector voltage, provided that the voltage is sufficiently high to produce saturation. This current then depends only upon the number of atoms striking the filament, or the vapor pressure, and accordingly can be used as a measure of vapor pressure.

The total number of positive ions is equal to the current divided by the charge per ion. From Eq. (32) this is

$$n = \frac{i}{e} = \frac{p}{\sqrt{2\pi mkT}}$$

By measurement of positive-ion currents at different bulb temperatures the relation between vapor pressure and temperature has been determined to be

$$\log_{10} p = 10.65 - \frac{3992}{T} \quad (35)$$

This evaporation of ions can take place to any large extent only at filament temperatures above 1200°K. At lower filament temperatures the rate of evaporation of the caesium is low and the ions are adsorbed on the surface. Then they become effective in lowering the work function, as already described. As soon as the work function has fallen below 3.88 volts, *i.e.*, below the ionizing potential of caesium, the positive-ion emission ceases.

34. Other Positive-ion Emitters.

If we consider the ionizing potentials of the other alkali metals and alkali earths, which are given in Table IV, we find that only caesium, potassium and rubidium have lower ionizing potentials than the work function of tungsten, so that these are the only elements which would

be expected to exhibit this behavior with tungsten. Platinum with a work function of 6.27 volts would give positive-ion currents with sodium and lithium as well. If a film of oxygen is adsorbed on tungsten, its work function is increased to 9.2 volts and accordingly ions such as copper, with an ionizing voltage below 9 volts, can be converted to positive ions.

35. Slat Anode.

Caesium atoms are very easily sputtered off of the filament surface by positive ions. This effect can be minimized by using an anode of the special form of construction shown in Fig. 16. The vanes *a* are all connected together and serve as anode. The vanes *g* are also connected together and serve as grid. Since they are at a lower potential than *a*, any positive ions which are formed in the space between *a* and

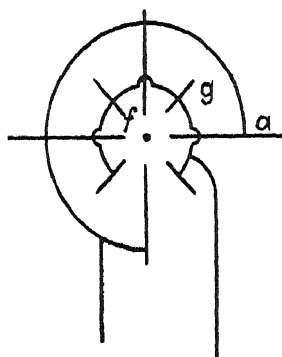


FIG. 16.—Slat anode.

g will be drawn toward *g* rather than toward the filament *f*, which is thus quite effectively protected from bombardment.

36. Technique.

The use of caesium in vacuum tubes involves a special technique. Owing to its great chemical activity the metallic caesium cannot be handled in air as is customary with sodium and potassium. It must be generated *in vacuo*. This can be done by heating a mixture of caesium chloride and calcium filings in a hard-glass tube by torching with a Bunsen flame. The calcium reduces the salt, setting free metallic caesium which can be distilled into the vacuum tube as required.

The caesiated filament is not the only possible source of positive ions. As has been pointed out, any gas or vapor having an ionizing potential less than the work function of a heated surface will evaporate from that surface as positive ions.

37. Positive-ion Emission from Catalysts.

Kunsman has found that certain catalysts which are used to promote the synthesis of ammonia from nitrogen and hydrogen are also emitters of positive ions. One of these catalysts is formed by fusing a mixture of very pure magnetite and 1 per cent of alumina with about $\frac{1}{2}$ per cent of alkali or alkali-earth metal. This material can be finely ground up and suspended in paraffin and applied to a filament in the same way as oxide coating. This material yielded measurable positive-ion currents at temperatures as low as 270°C . The relation between temperature and positive-ion current followed an equation of the Richardson form. The mass of the ions was found to be the same as that of the alkali or alkaline-earth metal.

38. Positive-ion Emission from Pure Metals.

A different type of positive-ion emission has been observed by Smith, who found that tungsten and molybdenum filaments emit positive ions even after the filaments have been heated to 3000°K . and then been well aged. This treatment would remove any traces of alkali which remained in the wire from the processing. Examination with the mass spectrograph showed that the ions were actually those of tungsten and molybdenum. The emission with temperature follows an equation of the Richardson form with $\phi = 6.55$ volts for tungsten and 6.09 volts for molybdenum.

39. Limitations of Various Emitters.

Each one of the various emitters discussed has advantages and limitations which make it particularly suitable for use in certain fields. Where energy considerations are not involved, pure tungsten is by far the simplest and most reliable type of cathode. It is particularly suited for kenotrons or x-ray tubes where extremely high voltages are involved, as there is no surface layer to be destroyed by positive-ion bombardment. The filament is not likely to be injured by excessive filament voltages short of burn-out.

The limitation of pure tungsten lies in its relatively low emission. In order to obtain large electron currents, it is necessary to use filaments with excessively large surfaces or to operate at extremely high temperatures which results in decreasing the useful life of the filament.

Thoriated tungsten has the great advantage over pure tungsten, of being a much more efficient emitter so that electrons can be obtained at a much lower cost in terms of energy input. Since the filaments can be operated at relatively low temperatures, it is possible to obtain a very long emission life. The limitation of the thoriated filament is its sensitiveness to minute amounts of oxidizing gases, so that it requires a good vacuum for successful operation. This handicap is removed to some extent by the process of carbonizing.

The coated filament is a very efficient emitter and furthermore lends itself to use in radiator-type cathodes which would be difficult to construct using thorium. The vacuum conditions required for its operation are somewhat less rigorous than for thoriated tungsten. In practice it has been found to stand up well in gaseous-discharge tubes.

The caesiated cathode is the most efficient type cathode known, but the fact that a low pressure of

caesium vapor is required for its operation limits its usefulness largely to the receiving-tube field. The presence of the vapor limits its use to relatively low voltages. Furthermore, because of the dependence of vapor pressure on temperature, the characteristics of the tube are somewhat affected by the temperature of its surroundings. The activity of this type of filament is liable to be destroyed by an overvoltage applied to the filament, since a filament temperature high enough to distill off the oxide layer permanently destroys the cathode.

TABLE III.—EMISSION CONSTANTS FOR CAESIUM

Caesium on tungsten	α	β	γ
Left-hand branch of curve.....	6.65×10^{14}	+31,300	-0 70
Right-hand branch of curve.	8.6×10^{-12}	-19,100	+1 66
Caesium on oxygen			
Left-hand branch of curve.....	1.04×10^{10}	+23,400	-0 62
Right-hand branch of curve ...	2.95×10^{-11}	-32,200	+1.96

TABLE IV.—IONIZING POTENTIALS FOR VARIOUS ELEMENTS

Element	Ionizing Potential
Lithium.....	5.37
Sodium.....	5.13
Potassium.....	4.10
Rubidium.....	4.10
Caesium.....	3.9
Barium.....	5.19
Strontium.....	5.67
Calcium.....	6.01
Magnesium.....	7.75

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CHAPTER V

SECONDARY EMISSION

40. The Phenomena.

Thermionic emission is only one of several processes by which the emission of electrons may take place. Another process which assumes considerable importance in some types of vacuum tubes is secondary or impact emission. The theory of this phenomenon is not so fully developed as that of thermionic emission.

If an electron strikes a metal surface at a sufficiently high velocity, the impact may cause other electrons to escape from the surface. These are called *secondary electrons*. The number of secondary electrons varies with the velocity of the impacting, or primary, electrons and with the chemical nature and the physical condition of the surface on which they strike.

The secondary emission from any given surface increases with increasing velocity of the primary electrons. Secondary emission may be observed for primary velocities as low as 20 or 30 volts. The number of secondaries per primary is rarely greater than 8 or 10 and is usually in the neighborhood of 2 or 3. Secondary emission is nearly independent of the temperature of the emitting surface, except in so far as changing the temperature alters the nature of the surface by sintering, recrystallization, freeing the surface from adsorbed gas films and the like. The secondary electrons are emitted with initial velocities of the order of a few volts. They are emitted in random directions.

41. The Observations.

When the number of secondary electrons emitted is less than the number of primaries, it is not possible to differentiate experimentally between secondaries and reflected primaries. However, when the number of secondaries exceeds the number of primaries, there is no doubt about the phenomenon. This will be evident from the discussion of the method of measurement, which follows. The phenomenon of secondary emission is readily observed in any three-electrode tube. If the grid of the tube is made more positive than the plate, it will receive a part of the electron current from the cathode while a part will pass between the grid meshes to the anode. The impact of these electrons on the surface of the anode may cause the liberation of secondary electrons. These will be attracted to the more positive grid. There will thus be a current of primary electrons

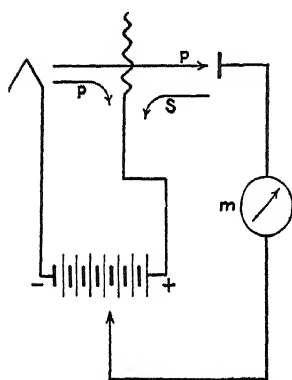


FIG. 17.—Circuit for observing secondary emission. P = primary electron current. S = secondary electron current.

to the plate and a current of secondary electrons from it. The net current to the plate, as measured by a meter m (see Fig. 17) in the plate circuit, will be the difference between the primary and secondary electron currents. It will be positive or negative, depending upon whether the number of secondaries emitted by each primary is less or greater than unity.

The circuit for making these measurements is shown in Fig. 17. At any constant value of grid potential, as the plate potential is increased, more and more electrons will succeed in passing through the grid and reaching the plate. The higher the potential of the latter, the greater

will be the velocity of these electrons when they strike it. When this velocity becomes high enough, the primary electrons will begin to cause the emission of secondary electrons. The number of secondaries emitted by each primary electron will increase as the primary velocity increases. All of these stages are shown in the

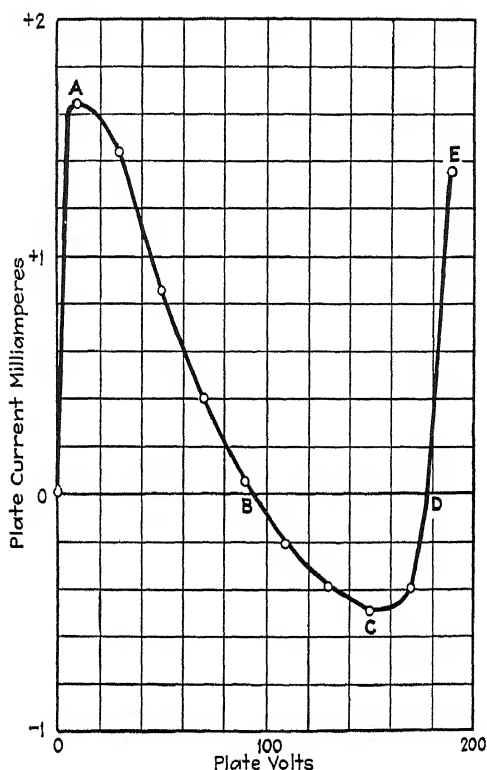


FIG. 18a.—Secondary emission from a caesium-coated silver oxide surface. Grid potential 200 volts.

plate voltage-plate current characteristic for constant grid voltage, shown in Fig. 18a. In the region *OA* the number of electrons which pass through the grid and reach the anode increases with increasing anode voltage. In the region *AB* the number of secondaries is increasing rapidly with increasing primary voltage so that the net current to the anode begins to fall off. At *B* every primary is causing the emission of one secondary.

Therefore, as many electrons are leaving the anode as are arriving at it, so that the net current to the anode is zero. From *B* to *C* the anode current reverses, because each primary causes the emission of more than one secondary so that more electrons are leaving the plate than are reaching it. The number of secondaries per primary reaches a maximum at *C*. As the anode voltage is increased still further, it approaches the grid voltage so that it captures relatively more primary

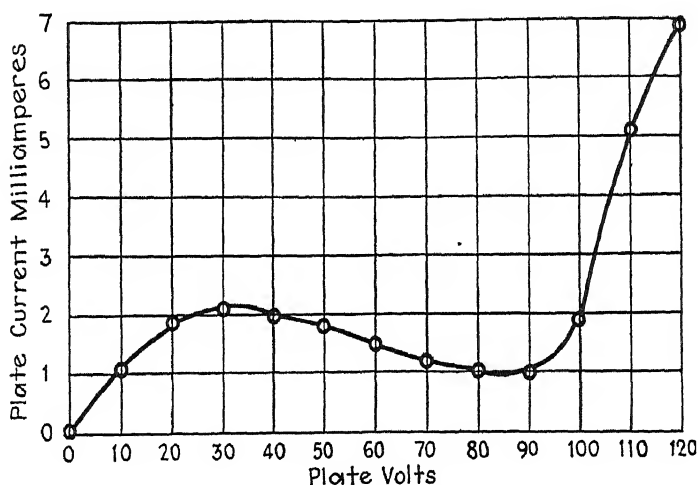


FIG. 18*b*.—Secondary emission from the anode of a U. X. 201 A. Radiotron. Grid potential 110 volts.

electrons and fewer secondaries escape to the grid. Accordingly the ratio of secondaries per primary decreases, and the current to the plate increases until it reaches saturation at *E*. Above *E* there is no field to pull electrons from the anode to the grid. If the ratio of secondaries to primaries does not exceed unity, the curve will not cross the *x* axis. The same general trend will be followed, however, as shown in Fig. 18*b*.

42. Quantitative Relations in Triodes.

A characteristic curve, such as that of Fig. 18*a*, does not give any indication whatsoever of the maximum

number of secondary electrons emitted by each primary, though the voltage of the point *B*, at which each primary electron causes the emission of a single secondary, is sometimes used as a qualitative comparison of the emitting power of various substances.

It is possible, however, to make simple measurements in any three-electrode high-vacuum tube which will yield approximate values of the ratio of secondaries to primaries. These consist in the anode current-anode voltage characteristics, discussed in Fig. 18*a*, and the

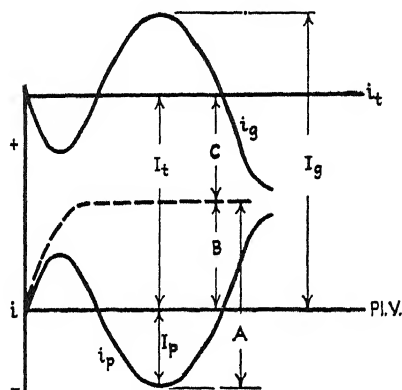


FIG. 19.—Determination of secondary to primary ratio. i_t = total current; i_g = grid current; I_g = maximum grid current; i_p = plate current; I_p = maximum plate current.

anode voltage-grid current characteristic. These curves are shown in Fig. 19. The grid current, when the anode voltage is 0, represents the total emission from the filament. If a horizontal line is drawn through this value, the grid characteristic with reference to this line will be a mirror image of the anode-current characteristic with reference to the x axis. The necessity for this will be evident from the fact that the sum of the grid and anode currents represents the total emission from the filament. The secondary current disappears in this sum, as it is always subtracted from the anode and added to the grid current. The grid current may and does exceed the total emission from the cathode whenever the ratio

of secondaries to primaries exceeds unity. Under these conditions the current to the grid consists of the electrons coming directly from the cathode plus the secondary current from the anode. Since the secondary/primary ratio is greater than unity, this is greater than the electron current from cathode to anode. The true primary current to the plate cannot be measured. It is less than the total current by the amount of the current intercepted by the grid. In the figure it is represented by the dotted line. The maximum observed grid current must equal the total current plus the number of secondaries received from the plate, or

$$\begin{aligned} A + C &= \text{maximum } i_p + i_t = \text{maximum } I_g \text{ (observed)} \\ B + C &= I_t \text{ (observed)} \\ \frac{A + C}{B + C} &= \text{maximum } \frac{I_g}{I_t} \end{aligned} \quad (36)$$

and is called *the observed ratio*.

This quantity is greater than A/B , which is the actual ratio. In other words, the ratio of I_g maximum to I_t is somewhat larger than the true ratio.

Another method has been devised for determining the secondary to primary ratio. This is based upon the experimental fact that the fraction of the total current intercepted by the grid is equal to the ratio of the projected area of the grid to the total area of the anode. This ratio is constant, provided that the plate potential is greater than two-tenths of the grid potential. Thus the secondary current is obtained from the observed minimum in the plate-current characteristic, and the primary current is calculated from the product of the observed total current and the geometrical ratio.

In general, highly polished metal surfaces yield more secondary electrons than rough (but clean) surfaces. Contamination of the surface by some foreign material usually increases the secondary emission.

The s/p ratios for a number of substances are:

Pure tungsten, molybdenum,*

nickel $s/p < 1$

Magnesium, calcium $s/p > 1$

Potassium, caesium $s/p = 2$ (approximately).

For compounds of alkalis and alkali earths the s/p ratio is about 3. These values are for primary voltages up to a few hundred volts. In general, heating and degassing of metal lower the secondary emission.

43. Effect of Secondary Emission on Vacuum-tube Operation.

In Pliotrons,† such as receiving tubes, with oxide-coated cathodes, the inside of the anode may become coated with barium evaporated from the cathode and so become a fairly good secondary emitter. In some power tubes, where high grid potentials are used, the secondary emission from the grid may cause the grid current to reverse so that electrons may flow to the anode from the grid. This may still further increase the grid potential until it approaches the anode potential, and blocking of oscillators and excessive heating of the grid and plate may result.

44. The Dynatron.

Secondary emission has been put to practical use in the Dynatron. This is essentially a pliotron with the grid placed as close to the anode as possible and the anode so treated as to be a good secondary emitter. When the grid is at a high positive potential and the plate is slightly less positive, some secondaries are emitted. As the plate voltage increases, the number of secondaries increases, so that the plate voltage - plate current characteristic has a negative slope corresponding to the portion

* Hyatt found a maximum value of $s/p = 1.15$ at 600 volts.

† A trade name of the General Electric Co.

AC in Fig. 18a. The plate current is decreasing with increasing voltage so that the circuit behaves like a negative resistance. Over a wide range this characteristic remains linear and can be described by the equation

$$i = \frac{E}{\bar{r}} + i_0 \quad (37)$$

where \bar{r} is negative. i_0 disappears if the Dynatron is connected in series with an e.m.f. just equal to the voltage at the crossover point B . For example, if the Dynatron is put in a box, and only two leads are brought out, one from the plate and one from the battery, having an e.m.f. just equal to the crossover voltage, it will behave like a negative resistance.

The negative-resistance characteristic makes it possible to use the Dynatron as an amplifier for either current or voltage. Assume an ohmic resistance R in series with the negative resistance \bar{r} of a Dynatron and a voltage E impressed across the combination. Let

I = current

e_R = drop across R

e_r = drop across \bar{r}

then

$$\begin{aligned} e_R &= IR \\ e_r &= I\bar{r} \\ E &= e_r + e_R = I(R + \bar{r}) \\ \frac{e_R}{E} &= \frac{R}{R + \bar{r}} \end{aligned} \quad (38)$$

By choosing suitable values of R and \bar{r} the voltage amplification may be made very high.

The Dynatron may also be used as a current amplifier by connecting it in parallel with an ohmic resistance R . Let

I = current in main line

i_R = current through ohmic R

i_r = current through dynatron

then

$$\begin{aligned} i_R &= \frac{E}{R} \\ \frac{i_R}{I} &= \frac{E/R}{E\left(\frac{1}{\bar{r}} + \frac{1}{R}\right)} = \frac{\bar{r}}{\bar{r} + R} \end{aligned} \quad (39)$$

By making $\bar{r} + R$ very small, large values of current amplification may be obtained.

The emission of secondary electrons from the surface of insulators is of great practical importance in some vacuum tubes. When high-velocity electrons impinge on an insulator such as a bulb wall, they may cause the emission of secondaries. If the s/p ratio is greater than one, the glass wall becomes positively charged. The wall thus continues to attract electrons and is subject to electron bombardment. This dissipation of energy at the walls may cause considerable local heating and even puncturing of the walls. This effect is most noticeable in x-ray bulbs and high-voltage Kenotrons.*

45. Magnetron.

The motion of electrons can be influenced by a magnetic field as well as by an electrostatic field. Tubes in which the electron current is controlled by a magnetic field are called *magnetrons*. In traversing a magnetic field the electrons are deflected at right angles to the direction of motion of the electrons and to the magnetic lines of force by a force directly proportional to their velocity and to the field strength. A particularly interesting case is that of a tube containing a straight wire filament in the axis of a cylindrical anode, with a uniform magnetic field which could be produced by a long solenoid wound around the tube, parallel to the axis.

In the absence of any magnetic field the paths of the electrons are radial lines from the cathode to the anode.

* A trade name of the General Electric Co.

When the magnetic field is applied, the electron paths become curved in the plane normal to the axis. If the voltage is kept constant, the curvature of the paths will increase with increasing magnetic field until they strike the anode almost tangentially. A further increase in magnetic field will cause them to miss the anode altogether and return to the filament. Thus at a certain critical magnetic field the current to the anode will drop abruptly from its saturation value to zero. The critical value of this field H at which this occurs is

$$H = \sqrt{\frac{8m}{e} \frac{V}{R}} = \frac{6.72V^{1/2}}{R} \quad (40)$$

where R = radius of the anode

V = anode voltage.

In the case of a straight wire filament the field produced by the filament current consists of magnetic lines of force which are circles around the filament. If the filament current is small, the effect of its field is in most cases negligible, but with large filaments, carrying currents of the order of 100 amp. or more, the effect of the field may become quite large. In this case the electrons, which would move to the anode in radial lines in the absence of a field, move in paths curved in planes through the axis. If the field is sufficiently strong, they are unable to reach the anode and return to the filament. The critical value of anode voltage at which this occurs is

$$V = 0.01882I^2 \left(\log_{10} \frac{D}{d} \right) \quad (41)$$

where I = filament current

D = diameter of anode

d = diameter of cathode.

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CHAPTER VI

DETERMINATION OF TEMPERATURE

46. Optical Pyrometry.

Since temperature is a very important factor in the thermionic emission of electrons it is necessary to determine the temperature of the emitting surface with a high degree of accuracy. The most accurate method is by optical pyrometry.

Essentially optical pyrometry consists in matching the brightness of the unknown surface with that of the filament of a standardized incandescent lamp. In the "disappearing-filament" type of pyrometer the filament of the lamp is viewed against the unknown surface (which may be another filament) as a background. When the two are at the same brightness, no line of demarcation is visible. This condition of balance is brought about either by interposing a calibrated absorbing screen between the standard lamp and the unknown surface, or else by varying the temperature of the standard by varying the current passing through it. The temperature of the filament of the standard lamp at different filament currents has been obtained by a previous calibration.

Pyrometry is the most accurate method of determining temperature, because the increase in brightness of a hot body with increasing temperature is about twelve times as large as the percentage change in temperature. The pyrometer reading does not give the true temperature directly but the brightness or black-body temperature from which the true temperature can be calculated by a simple formula.

47. Total Radiation.

In practice it is often difficult, if not impossible, to see the filament or cathode of an electron tube, and for this reason, as well as for convenience, other methods are used. The most satisfactory method is based upon measurement of the energy radiated, but, instead of visual observation of the radiation as in pyrometry, the total radiation is measured by observing the energy input to the filament.

In the simple case of a filament of resistance R , carrying a current I , the heat developed is I^2R . This will cause a rise in temperature of the wire until equilibrium is reached, and the heat developed is just balanced by the heat losses. These can take place only through the agency of convection, conduction and radiation. In a high vacuum, of course, there are no losses by convection. Conduction can take place only at the leads and it accounts for but a small part of the energy. Most of the heat loss therefore takes place by radiation. A small percentage of this radiant energy is in the form of visible light; the remainder, of course, is infrared.

The total amount of energy radiated from a unit area of filament surface in a high vacuum (per second) depends only upon the nature of the surface and the temperature. This is expressed by the well-known fourth power law

$$\eta = e_t \sigma T^4 \quad (42)$$

where e_t , the emissivity of the surface, is a constant depending upon the nature of the surface. It is always less than unity except for a perfect radiator or black body for which its value is unity. It increases with increasing temperature. Table V gives values of e_t for several metals at several different temperatures. σ , the Stefan-Boltzmann constant, is 5.722×10^{-5} erg per

square centimeter per second per degree. T is the absolute temperature.

If σ , e and T are known, we can calculate the total energy radiated from a unit area of filament surface at

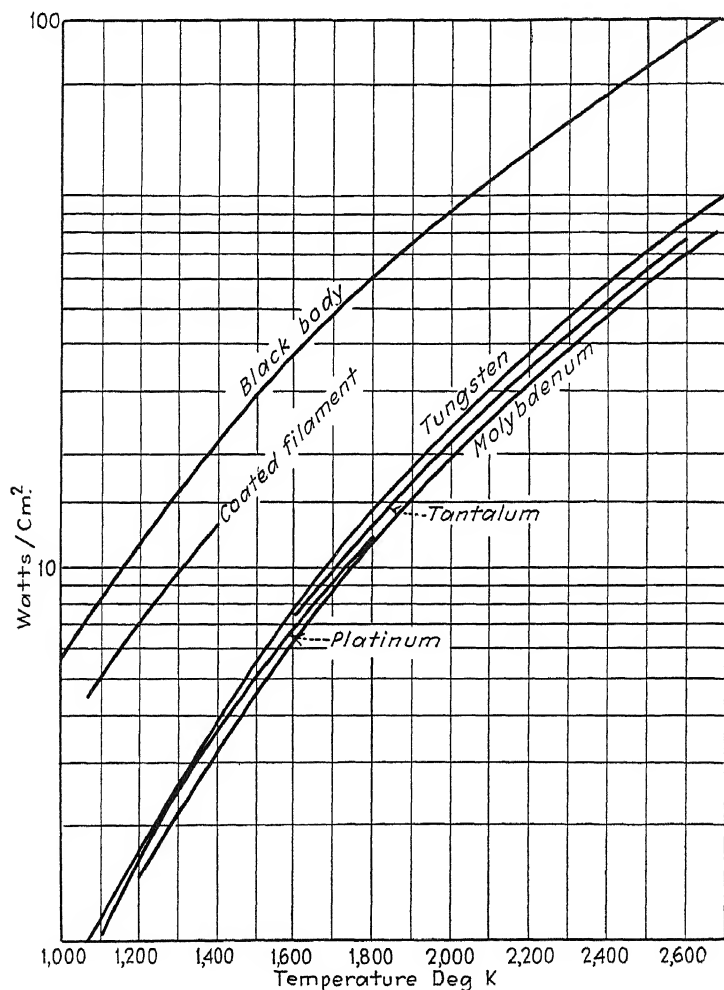


FIG. 20.—Energy radiated from various metal surfaces as a function of temperature.

any temperature. The energy radiated per unit area must equal the energy input divided by the surface. Once having this value, it is possible to reverse the process and to determine the temperature at which a

filament is operating from the energy input and the dimensions. For

$$\eta = e_i \sigma T^4 = \frac{EI}{\pi dl} \quad (43)$$

In Fig. 20 are plotted curves showing the relation between η and T for a black body, a coated filament, tungsten, tantalum, molybdenum and platinum. The temperature of a filament then can be found by dividing the total energy input by the area to obtain η . The corresponding value of T can then be read from the curve. Worthing and Forsythe give the following empirical relation between the energy radiated from tungsten (in watts per square centimeter) and the temperature:

$$\log_{10} E = 3.680 (\log_{10} T - 3.3) - \frac{1040}{T} + 1.900 \quad (44)$$

48. Specific Characteristics.

The total energy radiated per unit area furnishes a very accurate method of determining the temperature of a filament as it varies with the fourth power of the temperature. Thus a small change in temperature results in a large change in radiation. Other characteristics may also be used, since the characteristics are related in a very simple way to the physical dimensions. Among these characteristics are the energy radiated per unit area, which has just been discussed; the resistivity per unit length; and the current for a filament of unit cross section (for circular cross section). These characteristics are all specific functions of temperature, and if the values are known for any one filament size they may readily be calculated for any other filament size. The relations between these characteristics and the filament dimensions may be derived as follows. Let

ρ = resistivity

η = radiation intensity

r = radius

L = length.
 W = wattage
 R = resistance
 V = voltage
 I = current

Then

$$W = 2\pi r L \eta \quad (45)$$

$$R = \frac{\rho L}{\pi r^2} \quad (46)$$

$$V = \frac{\rho L I}{\pi r^2} \quad (47)$$

$$V = \sqrt{WR} \quad (48)$$

$$I = \sqrt{\frac{W}{R}} \quad (49)$$

The following examples illustrate the use of these functions.

Two filaments of different diameters, which are required to operate at the same temperature, must satisfy the condition that both radiate the same number of watts per unit area:

$$\frac{I_1^2 R_1}{2\pi r_1 L_1} = \frac{I_2^2 R_2}{2\pi r_2 L_2}$$

If we make L_1 equal to L_2 , this reduces to

$$\frac{I_1^2 R_1}{r_1} = \frac{I_2^2 R_2}{r_2}$$

and since

$$\frac{R_1}{R_2} = \frac{r_2^2}{r_1^2}$$

therefore

$$\frac{I_1}{I_2} = \left(\frac{r_1}{r_2}\right)^{3/2} \quad (50)$$

Similarly, the relation between voltage and dimensions for *any* two filaments operating at the same temperature are

$$\frac{V_1}{V_2} = \left(\frac{r_2}{r_1}\right)^{1/2} \frac{L_1}{L_2} \quad (51)$$

The relative amounts of energy required for any two filaments operating at the same temperature are

$$\frac{W_1}{W_2} = \frac{r_1 L_1}{r_2 L_2} \quad (52)$$

The relative dimensions for two filaments which are required to operate at the same temperature and voltage are

$$\frac{r_1}{r_2} = \left(\frac{L_1}{L_2}\right)^2 = \left(\frac{W_1}{W_2}\right)^{\frac{2}{3}} = \left(\frac{I_1}{I_2}\right)^{\frac{2}{3}} \quad (53)$$

A requirement which is often made in life-testing vacuum tubes or incandescent lamps is that the temperature of the filament shall remain constant, even though the diameter of the filament is reduced by vaporization. This condition is satisfied by the relation

$$\frac{I_1^{\frac{1}{2}} V_1}{L_1} = \frac{I_2^{\frac{1}{2}} V_2}{L_2} \quad (54)$$

Characteristics such as the current, resistance and watts per unit area are specific characteristics of a filament. These have been very carefully determined by a number of investigators and summarized by Worthing and Forsythe. Table VI gives some of the more important characteristics for the case of tungsten.

49. Critical Summary.

As has already been pointed out, the watts per square centimeter is the most accurate of the above criteria of temperature since it increases with the fourth power of temperature. Therefore a very small change in temperature results in a large change in η . It involves, however, an accurate knowledge of the filament dimensions.

If the filament diameter is the only dimension which is known, the current is a very useful measure of the temperature.

The value of $VI^{1/3}/L$ is particularly useful where the diameter is not known or is changing in value, as referred to above.

The resistance is perhaps the least accurate function since it has a low temperature coefficient. However it is the only one of the characteristic functions which is of value in the presence of gas, where the heat losses are due to conduction and convection as well as radiation. It also has the advantage of being entirely independent of the surface condition of the filament, which materially alters its thermal emissivity.

In the case of materials having a high temperature coefficient of resistance, such as tungsten, the ratio of hot to cold resistance is also a useful criterion of temperature. For tungsten

$$\frac{R}{R_0} = \left(\frac{T}{T_0} \right)^{1.2} \quad (55)$$

This value of the hot to cold resistance ratio at known temperatures is often used as a convenient means of identifying the material of an unknown filament. In making use of resistance it must be kept in mind that both resistance and temperature coefficient of resistance are extremely sensitive to traces of impurities. For instance, 0.1 per cent of carbon increases the resistance of tungsten at room temperature by 5 per cent.

A practical consideration in the use of resistance is that in many cases the resistance of the filament is low in comparison with the leads and contacts. This makes resistance measurements almost valueless for very short filaments.

50. Lead Losses.

Thus far in this discussion it has been assumed that the entire filament is at a uniform temperature. In practice this is never the case, as visual observation

readily shows. The temperature is at a maximum near the center of the filament and is less near the ends where the heat losses are large, due to the thermal conductivity of the relatively heavy lead wires. This temperature

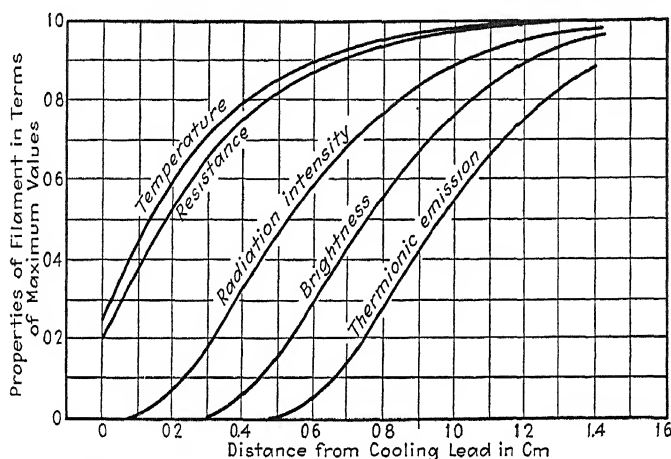


FIG. 21.—Effect of the leads upon various properties of tungsten filaments.

gradient alters all the characteristics of the filament. Due to the cooling of the ends, their resistance is lowered and the voltage drop across the filament is less than it would be for an ideal uniformly heated filament. Simi-

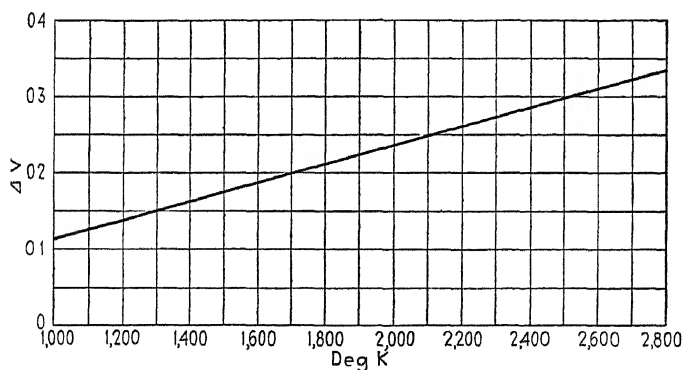


FIG. 22.— ΔV as a function of temperature.

larly, the brightness and the electron emission are less than they would be for a uniformly heated filament. Semiempirical methods have been developed for correcting for these *lead losses* as they are called. Since the

different characteristics vary in different ways with temperature, the correction factor to be applied depends upon the particular property which is under investigation and the manner in which that property varies with temperature. Figure 21 shows how the various properties of a tungsten filament, expressed in terms of the maximum value at the mid-point of the filament, vary with distance from the leads. The effect is very large in the case of a property such as thermionic emission, which varies exponentially with temperature.

The correction factor by which the observed value has to be multiplied to give the value for an ideal filament with no end losses is obtained from the formula

$$f = \frac{V + 2\Delta V}{V + 2\Delta V - 2\Delta V_H} \quad (56)$$

where V = observed voltage drop across the filament
 ΔV = actual decrease in voltage due to the cooling of a single lead
 ΔV_H = volt equivalent decrease in the property under consideration.

Values of ΔV corresponding to different filament temperatures are shown in Fig. 22. ΔV_H can be calculated from the empirical equation

$$\Delta V_H = P\left(\frac{T_m}{1000}\right) - Q\left(\frac{T_0}{1000}\right) - R \quad (57)$$

where T_m and T_0 are the temperatures of the filament at the center and at the lead, respectively; and P , Q and R are given by Table VII.

51. Radiation Emissivity.

Where temperature is determined by measurements of energy radiated, it is of the utmost importance to know the radiation emissivity accurately. This depends not only upon the chemical nature of the surface but

upon its physical condition as well. Any roughening of a surface tends to increase its emissivity and make it approach black-body conditions. It is thus possible that ion bombardment may tend to increase the emissivity of a surface while sintering may tend to decrease it. Oxide-coated filaments prepared by various processes show a considerable range in emissivity although the surfaces are all the same chemically. An average value for the emissivity of oxide-coated filaments is 0.70. This is very much higher than the value for any of the pure metal filaments, such as tungsten, tantalum, molybdenum, platinum or nickel.

The process of carbonizing a tungsten filament increases its emissivity. The emissivity of a carbonized tungsten filament is approximately 1.2 times that for pure tungsten. A thoriated filament does not differ in emissivity from pure tungsten nor does a monatomic film of any kind affect the emissivity of the underlying surface.

52. Radiator Cathodes.

An interesting example of the advantage to be gained by a proper understanding of emissivity is the radiator type of coated cathode. The ordinary type of radiator cathode coated on the outside has practically the same efficiency (on an energy basis) as an oxide-coated filament. If this same cathode is coated on the inside instead of on the outside of the cylinder, its efficiency is increased threefold. This is because the thermal emissivity of clean nickel is 0.15, while that of the coated surface is approximately 0.75. If we assume that the open end of the cylinder has an emissivity of 1 and its area is 0.1 of the total, while the side has an area of 0.9 and an emissivity of 0.75, then the total heat loss for the outside-coated cathode would be

$$0.1 \times 1 + 0.9 \times 0.75 = 0.775 \text{ watt}$$

If the same cathode is coated on the inside instead of on the outside, the heat loss would be

$$0.1 \times 1 + 0.9 \times 0.15 = 0.235 \text{ watt}$$

or approximately one-third of its former value.

The radiation can be further reduced by surrounding the cathode with heat-reflecting nickel cylinders, as shown in Fig. 23. A cylinder surrounding the cathode reflects back a portion of the heat and so reduces the heat losses. If E is the heat necessary to maintain a black body of the same size at the same temperature as the inner cylinder, the effect of brightly polished cylinders will be to reduce this loss to

$$\frac{eE}{2k - 1 - (k - 1)e} \quad (58)$$

where e = emissivity of the surrounding surfaces

k = number of surfaces.

When e is small, this reduces to

$$\frac{eE}{(2k - 1)} \quad (59)$$

Three such cylinders reduce the radial heat flow to 4 per cent of that from an oxide-coated surface. By coating a set of

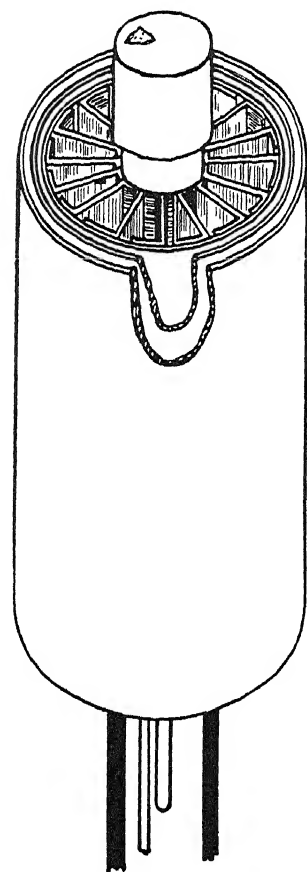


FIG. 23.—Heat-shielded cathode. (A. W. Hull, *Gen. Elec. Rev.*, **32**, 213, 1929.)

vanes, as shown in the figure, the effective electron-emitting area may be greatly increased without increasing the radiating surface, which results in greatly increased emission efficiency. This type of cathode is

not suitable for high-vacuum tubes, as space charge limits the current which can be drawn from the cells of the cathode. In gas-filled tubes where positive ions are present, this limitation is not imposed.

53. Comparison of Emitters.

In comparing different emitters where the question of efficiency is involved, the comparison cannot be taken as the ratio of the emission currents per unit area for surfaces at the same temperature because the radiating properties of the two surfaces may differ. Thus, at the same temperature, the surface having the higher thermal emissivity (*i.e.*, the one which is the better heat radiator) requires a larger energy input to maintain its temperature. Its efficiency is lower than would be the case if its thermionic properties were the same, but its heat-radiating properties were decreased. Thermionic emitters should therefore be compared in terms of amperes emission per watt of input at the same number of watts input per unit area.*

For example, the emission from a tungsten filament completely covered with thorium at a temperature of 2000°K . is 2.75 amp. per square centimeter. The energy radiated at this temperature is 24.1 watts per square centimeter. The efficiency of emission, therefore, is $2.75 \div 24.1 = 0.114$ amp. per watt at 24.1 watts per square centimeter. The emission from a carbonized thoriated-tungsten filament at the same *temperature* is, of course, nearly the same, but, since the carbonized tungsten is a better radiator than the pure tungsten, more energy is required to maintain it at the same temperature. Since its emissivity is 1.2 times that of tungsten, the watts input at 2000°K . is 28.8 watts per square centimeter, so that the efficiency of emission is $2.75 \div$

* In practice, thermionic emitters are usually compared at the watts per square centimeter which give the same emission life.

28.8 = 0.095 amp. per watt at 28.8 watts per square centimeter (corresponding to 2000°K). The question which really is of importance practically is: What is the emission per watt at the same *wattage* input for the two filaments? A wattage input of 24.1 watts per square centimeter corresponds to a temperature of 1940°K. for the carbonized filament. At this temperature its emission is 1.742 amp. per square centimeter. The efficiency of emission is therefore $1.742 \div 24.1 = 0.0714$ amp. per watt. This value is the one to be compared with the value 0.114 amp. per watt for the uncarbonized filament.

TABLE V.*—TOTAL EMISSIVITY AT DIFFERENT TEMPERATURES FOR TUNGSTEN, MOLYBDENUM AND PLATINUM

Metal	Total emissivity ϵ , at		
	1000°K.	1500°K.	2000°K.
Tungsten.	0 114	0.192	0.260
Platinum	0 134	0 192	
Molybdenum.	0 096	0 157	0 210

* "International Critical Tables," McGraw-Hill Book Company, Inc., New York, 1929.

TABLE VI.*—SPECIFIC CHARACTERISTICS OF A TUNGSTEN FILAMENT 1 CM. LONG AND 1 CM. IN DIAMETER MOUNTED IN A VACUUM

Temperature, degrees Kelvin	Resistance, ohms	Potential drop, volts	Current, amperes	Power, watts	$V\sqrt{I}$
1000	32.73×10^{-6}	8.23×10^{-3}	0.251×10^3	2 068	51.9×10^{-3}
1200	40 80	14.77	0 362	5 35	105 3
1400	49.10	24.5	0 494	12 12	194 0
1600	57 60	37.7	0 655	24 72	328 0
1800	66 35	54.9	0 827	45 35	515 0
2000	75.20	75 5	1 004	75 8	756 0
2200	84 40	100 4	1 190	119 5	1064.0
2400	93 65	129 4	1 383	179 0	1442 0
2600	103 2	164 1	1.590	260 8	1915 0
2800	112 7	203.0	1 800	365.5	2470 0
3000	122 5	247.7	2.020	501.0	3130 0

* Worthing and Forsythe.

TABLE VII.*—CONSTANTS IN FORMULA FOR LEAD-LOSS CORRECTION FOR TUNGSTEN FILAMENTS

H	P	Q	R	Range, T_m °K.	Range, T_0 °K.
Voltage	0.154	0.081	0.056	1000-2500	Any value
Candle power	0.338	0.182	-0.004	600-3500	300-1400
Electron emission	0.440	0.158	0.072	1000-3500	300- 900
Watts radiated	0.293	0.160	0.084	1100-3000	300- 900

For voltage (watts input) a term, $-2.1 \times 10^{-8} T_0 \times T_m$ is to be added to the right-hand side of Eq. (57).

* DUSHMAN, S, Thermionic Emission, *Rev. Mod. Phys.*, **2**, 391, 1930.

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CHAPTER VII

GETTERS AND CLEAN-UP OF GASES. GASES IN METALS

54. Deleterious Action of Gases.

In order to function reliably it is of the utmost importance that vacuum tubes be exhausted to, and maintained at, a high degree of vacuum. The presence of even very small amounts of gases is harmful, owing either to their direct effect on the cathode or to their effect on the character of the electron discharge through space. The gases may "poison" the electron emission from the cathode by oxidizing it, or, in the case of inert gases, positive ions formed by collision with electrons may sputter the active material off the cathode surface and so deactivate it. The effect of positive ions on the electron discharge itself is to neutralize the space charge and fundamentally alter the characteristics of the tube. This will be discussed in Chap. VIII.

In order to obtain a high vacuum it is necessary, first, to free all parts of the tube from occluded gases; second, to pump out as far as possible all gas from the tube; third, after sealing off the tube from the vacuum system, to reduce the residual gas pressure still further by chemical or electrical means.

55. Gases from Glass.

The walls of glass bulbs give off large quantities of gas upon heating. This is very largely water vapor with a small admixture of carbon dioxide and nitrogen. On heating at any temperature, there is a large evolution of

gas which gradually ceases. On heating to a higher temperature, more gas is given off. The amount and nature of the gas evolved vary with the nature of the glass, and different methods of treatment are practiced in order to remove it. In general, it is necessary to heat the glass walls of any vacuum tube at temperatures varying from 360°C. for soft glass to 500°C. for hard glass for a considerable time in order to insure that no more gas will be evolved during the life of the tube. If this bake-out is not properly carried out, there will be a gradual evolution of gas from the walls of the bulb during the operating life.

56. Gases from Metals.

The metal parts used for electrodes contain large amounts of gas in solution as well as gases adsorbed on the surface. These gases are removed in part by treatment before the tube is exhausted and in part by a special procedure during the exhaust.

In the case of molybdenum, which has been studied more in detail than any of the other metals, Norton and Marshall found it necessary to heat the metal to 1760°C. in a vacuum of the order of 0.001 micron for a time which varied linearly with the thickness, in order to reach a condition where no more gas is evolved by the sample. When the metal is first heated, hydrogen is given off very readily at the lower temperatures. Carbon monoxide is given off at temperatures in the neighborhood of 1000°C. At higher temperatures the gas given off is very largely nitrogen. Grease and dirt on the surface of the metal usually increase the percentage of carbon monoxide in the gas which is evolved.

The gas evolution from molybdenum is greatly affected by the method used in cleaning it. The most effective method is electrolysis in concentrated sulphuric acid. Dipping in caustic, or filing the surface clean and washing in benzol, is less effective. Contamination of the surface

of the metal is a source of a great deal of the gas, and, if the metal has once been degassed, it will stay degassed if precautions are taken to keep the surface clean. A carefully cleaned sample of molybdenum weighing 5.1 g. gave off 21.4 cu. mm. of gas (measured under normal conditions of temperature and pressure) when heated to $1760^{\circ}\text{C}.$ for 20 min. The composition of the gas was 95 per cent nitrogen and 5 per cent carbon monoxide.

The amount of gas contained in tungsten ranges from 15 to 25 per cent of that obtained from a similar sample of molybdenum. In order to degas tungsten at a rate comparable to molybdenum at $1800^{\circ}\text{C}.$, it is necessary to heat the tungsten to $2300^{\circ}\text{C}.$

Nickel cannot be heated to much above $1030^{\circ}\text{C}.$, owing to its high rate of evaporation. At this temperature the gas evolved is largely carbon monoxide.

Graphite can be degassed at $2150^{\circ}\text{C}.$, so that on subsequent heating at a higher temperature no further gas is evolved. At the higher temperatures the gas evolved from graphite is predominantly nitrogen.

Hydrogen firing before exhausting is very effective in reducing the gas content of most metals. This consists in heating the metal to a temperature of about $950^{\circ}\text{C}.$ in an atmosphere of hydrogen for about 10 min.

In exhausting vacuum tubes the metal parts are cleaned as carefully as possible by one of the methods outlined above before sealing in. After the tube has been baked out to remove the gases from the glass walls, the metal parts are heated to incandescence by high-frequency induction or by electron bombardment. The filaments likewise are degassed by operating them at as high a temperature as possible for a considerable period.

57. Clean-up by "Getters."

No matter how well a vacuum tube has been exhausted, there always remains a small residual pressure of gas.

This may perhaps be of the order of 0.0001 mm. of mercury in commercial tubes. Even at this low pressure the number of molecules per cubic centimeter reaches the astounding figure of more than 10^{12} . Two methods are in use for reducing the pressure still further, chemical clean-up and electrical clean-up. The chemical clean-up takes place through the agency of a "getter." This is a substance which is usually volatilized on to the surface of the bulb wall just before the tube is sealed off from the vacuum system.

The getters most commonly used at present are phosphorus, calcium, magnesium, barium, strontium, aluminum and various mixtures or alloys of these. Phosphorus is used in the red form. This is quite inert, but, when it is vaporized from the surface of the filament or one of the electrodes, the vapor condenses as the active yellow form.

Barium and strontium are very active getters but have the disadvantage of oxidizing rapidly when exposed to air so that it is difficult to introduce them in a tube without having them completely oxidized. For this reason they are often used in the form of alloys with aluminum, which are quite stable in air and from which the active metal can be vaporized by heating, after exhausting the tube.

The alkali metals are extremely active getters, but the fact that their vapor pressure is high limits their usefulness to tubes where a small pressure of alkali-metal vapor is not harmful.

The getter is effective both in the chemical and in the electrical clean-up. In part, the gas reacts chemically with the getter. This is particularly true in the case of water vapor, oxygen and carbon dioxide. In part the gases are simply adsorbed and held as a monatomic layer on the surface of the getter. The getter not only functions at the time that it is vaporized, but it continues to take up gases which may be evolved during the life of the tube.

The getter may function in several different ways. At the instant of vaporizing it, there is a high vapor pressure of getter in the bulb and there will be collisions between the molecules of the residual gas and those of the getter. Chemical combination may take place at these collisions, and the resultant products will be deposited on the bulb wall. In this way some of the gas is removed.

After the getter has been condensed on the bulb wall, since its pressure is negligible, any further clean-up is due to the adsorption of the molecules which strike the walls. The formation of a monatomic layer of gas molecules on the surface of the getter may account for a great reduction in pressure. For example, a monatomic layer of oxygen formed over a surface of 10 sq. cm. will consist of 10^{16} molecules. This same number of molecules, if they occupied the volume of a 100-cc. bulb, would give a pressure of 3×10^{-3} mm., a relatively high pressure. The action of the getter, however, does not necessarily stop when a monatomic film has been formed on the surface, since diffusion may take place into the getter. Most getters are effective in clean-up, roughly in the order of their chemical activity.

The activity of getters is greatly increased by previously degassing them. In the case of receiving tubes the getter is usually fastened to the anode, from which it evaporates when the latter is heated by high-frequency induction before the tube is sealed off. In the case of large power tubes this method is not suitable, because the anodes are given a prolonged heat treatment and the getter would become saturated with gas long before the tube is ready to be sealed off. In such cases the getter is placed on an auxiliary electrode which can be heated separately at the end of the exhaust process.

58. Electrical Clean-up.

In the case of electrical clean-up, an electron current is drawn to the anode under the influence of a potential

of 100 or 200 volts. This is sufficient to form ions by collisions between electrons and gas molecules. The ions acquire fairly high velocities in the electric field and are actually driven into the walls of the bulb or the metal electrodes. While this can take place in well-exhausted tubes where no getter is present, it is greatly facilitated by the presence of a getter on the exposed surfaces. The ions formed also react chemically with the getter.

59. Quantitative Aspects.

The effects of low pressures of gas in vacuum tubes are often underestimated, possibly because of the small units in which the pressure is ordinarily stated. If a bulb having a volume of 250 cc. contains a gas at a pressure of 0.01×10^{-3} mm. of mercury, the total number of molecules of gas present is 10^{14} . Assuming that the gas is oxygen having a molecular diameter of 3×10^{-8} cm., if all the molecules were adsorbed on a surface in a layer one atom deep, they would cover an area of approximately 0.1 sq. cm. This area is comparable with, if not greater than, the filament area in most vacuum tubes of this volume, so it can readily be seen that even a very low gas pressure may have a tremendous effect upon filament emission.

Even at very low pressures a surface can become coated with a layer of gas in a very short time, owing to the high velocities of the gas molecules. The number of molecules of any gas which strike upon a unit area per second is given by the expression

$$n = \frac{p}{\sqrt{2\pi mkT}}$$

where p = pressure in baryes

m = mass of a molecule

T = temperature in degrees Kelvin

k = Boltzmann constant 1.37×10^{-16} erg per degree.

In the case of oxygen at the pressure of 0.01×10^{-3} mm. (1.3×10^{-2} barye), the number of molecules striking a unit area of surface in 1 sec. would be 3.5×10^{15} . Thus, in a large volume of gas at this pressure a filament would be completely covered with a monatomic layer of gas in $\frac{1}{3}$ sec.

60. Cathode Sputtering.

The operation of a thermionic tube is greatly affected by the presence of gas. The effect of the gas on the type of the discharge will be discussed in Chaps. VIII and IX. The effect on the cathode itself is also very important. The most noticeable feature of the bombardment of a cathode by positive ions* is the cathode sputtering. The positive ions, owing to their high values of kinetic energy, are able to knock off small particles of the cathode and so cause its disintegration. This cathode sputtering must not be confused with vaporization of the cathode due to the heat of the bombardment. Small particles consisting of aggregates of many molecules are actually torn from the cathode by the action of the ions. The size of the particles depends upon the conditions of voltage, gas pressure, nature of the gas and of the cathode surface. Since cathode sputtering is dependent on the high values of kinetic energy of positive ions, it can take place only under conditions which favor large values of the cathode drop. These conditions are cold-cathode glow discharges, or low values of thermionic emission in hot-cathode arcs.

At voltages below 1000 volts, the number of atoms sputtered per positive ion is less than one. As the voltage is increased, however, and the energy of the ion is raised, this ratio becomes larger. For glow discharges the lower limit of voltage, or threshold, is between 300 and 600 volts, depending on the cathode material and

* See Chap. IX for discussion of formation of positive ions.

the pressure and nature of the gas. The rate of sputtering is not appreciably affected by the temperature of the cathode. The order of the ease of sputtering of metals in descending order is bismuth, silver, platinum, palladium, iridium, antimony, rhodium, copper and nickel. Aluminum does not sputter readily and for this reason is often used for electrodes in gaseous-discharge tubes.

Positive ions are effective in the order of increasing atomic weights. Thus argon, neon and helium are effective in descending order. There are, however, many exceptions to this rule, particularly among the metal ions.

Aside from the phenomena of disintegration the cathode sputtering of activated cathodes presents some unusual aspects. Where the bombardment by the gas removes active materials from the surface of the cathode the latter becomes deactivated with a consequent drop in emission. This is a very common phenomenon in poorly exhausted thoriated-filament tubes where the emission gradually falls off while the anode voltage is on. The filament recovers again if the anode voltage is turned off and thorium is given an opportunity to diffuse to the surface again.

This effect has been exaggerated in some investigations by Hull. In the case shown in Fig. 24, argon at a pressure of 0.03 mm. was introduced into a thoriated-filament tube. As the anode voltage was increased, the current increased rapidly up to about 25 volts. Beyond this point the current decreased with increasing voltage, eventually falling to the value characteristic of pure tungsten. This effect was due to the removal of the thorium (by the sputtering action of positive argon ions) more rapidly than it was replaced by diffusion. This deactivation process by sputtering begins at an anode voltage of approximately 25 volts for argon. For mercury the critical voltage is 22 and for neon 27 volts.

This represents the kinetic energy which an atom of each of these gases must possess in order to be able to knock a thorium atom from the surface of a hot tungsten filament. Kingdon and Langmuir determined the critical values by a somewhat different method for cold filaments and found the values 45, 47 and 55 volts for neon, argon and mercury, respectively. The practical operation of activated cathodes in the presence of gas is made possible by

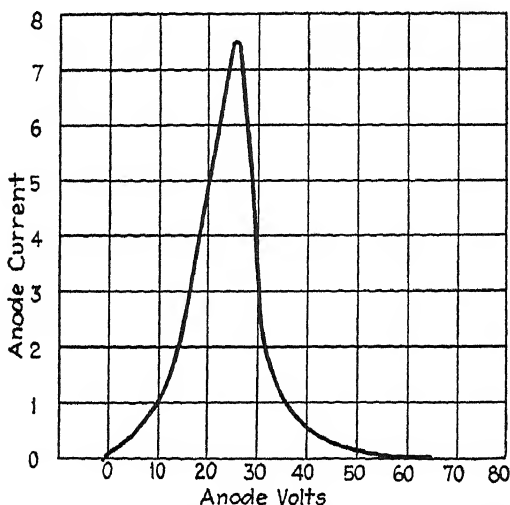


FIG. 24.—Deactivation of thoriated cathode by sputtering in argon.

operating conditions such that the cathode drop lies below these critical disintegration voltages.

61. Crystal Structure of Filaments.

The important rôle which the physical structure of the cathode plays in the operation of vacuum tubes is often not realized because the structure is only apparent upon examination by microscope. The ductility of tungsten and other materials used for filaments is due to the fact of their fibrous structure. Figure 25 shows a longitudinal section of a tungsten filament highly magnified. This is the so-called *raw wire* as it comes from the manufacturing process. The process of *working* by which this structure

is arrived at is discussed in standard texts on metallurgy. When a filament having a fibrous structure is heated above a certain temperature (called the *equiaxing temperature*), its structure changes from fibrous to granular, as

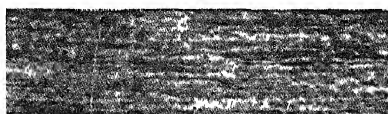


FIG. 25.—Longitudinal section of raw tungsten filament showing fibrous structure.

shown in Fig. 26. This change is not dependent on temperature alone but is a function of temperature and time. The long fibers tend to break up and form small grains which gradually increase in size with time. Below this temperature the structure of the wire is relatively stable.

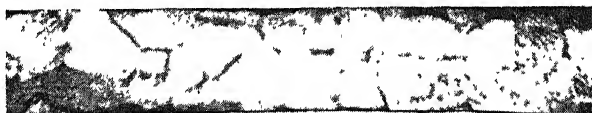


FIG. 26.—Longitudinal section of equiaxed thoriated tungsten filament showing granular structure.

The final size of the grains is determined in part by the chemical nature of the filament and in part by the treatment which it has received in the wire-drawing process, as well as by the subsequent heat treatment. A small percentage of thoria has the peculiar property of inhibit-



FIG. 27.—Longitudinal section of pure-tungsten filament (given same treatment as section shown in Fig. 26) showing large grains.

ing the growth of crystals in tungsten filaments. In fact, thoria was first introduced into incandescent lamp filaments for this purpose. Figure 27 shows a longitudinal section of a pure-tungsten filament which has received the same heat treatment as the thoriated fila-

ment shown in Fig. 26. The larger size of the grains is plainly evident. This change from a fibrous structure to a crystalline one changes the wire from a ductile to a brittle condition. The crystal structure of the wire influences the thermionic emission, as has been discussed in Chap. II. By suitable treatment it is possible to grow grains of the entire cross section of the wire and several centimeters long.

62. Burn-out of Filaments.

The life of vacuum-tube cathodes is in some cases determined by electron emission. In other cases it is limited by the burning out of the filament. This is due to the evaporation of the filament material which reduces the diameter of the wire. Some local irregularity usually results in a slightly greater reduction in diameter at that point. Since the same current passes through this portion as through the rest of the wire, this place runs at a higher temperature, thus aggravating the condition. Eventually the wire burns out at this point. As a rule burn-out takes place when evaporation has reduced the diameter by 10 per cent.

In the case of gas-filled tubes, burn-out may be due to another cause. A decrease in emission from the filament will result in an increase in the cathode drop. This will result in increasing the velocity of the positive ions that are bombarding the cathode surface, thus making the positive ions more effective in sputtering the cathode surface. When enough material has been sputtered from the cathode to reduce its diameter appreciably, it will burn out owing to local overheating.

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CHAPTER VIII

SPACE CHARGE

63. The $\frac{3}{2}$ Power Law.

The earliest experiments on electron emission were made under relatively poor vacuum conditions. As vacuum technique was improved, it became possible to make measurements in a high vacuum. Under these conditions it was found that the thermionic currents were smaller than when a slight amount of gas was present. This led the observers to the conclusion that electron emission did not take place except in the presence of gases, *i.e.*, that the gas was one of the primary causes of the emission. This erroneous conclusion was the result of making measurements at too low an anode

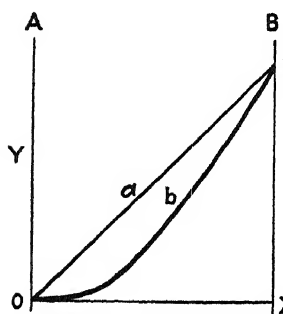


FIG. 28.—Potential distribution between parallel planes.

voltage. We now know that in the presence of gas the positive ions which are formed greatly increase the current which can pass between two electrodes at a given voltage. In the absence of gas, a higher voltage is required to draw the same current to the anode. A lack of understanding of this relation between current and voltage led to a misinterpretation of the rôle played by the gas. This effect was first explained by Langmuir, who derived the theoretical relation between the voltage applied between a pair of electrodes and the resulting electron current in a high vacuum. The same formula had been previously derived

by Child for the case of currents carried by positive ions in arcs at low pressures.

Let us assume two infinite equipotential parallel planes A and B , represented by A and B in Fig. 28. A emits electrons with zero velocity and accordingly serves as cathode. Let B be maintained at a positive potential with respect to the cathode. Let us measure the distance from the cathode along OX and the potential with respect to the cathode along OY . If no electrons are emitted from the cathode the potential between the two plates will vary linearly along OaP ; *i.e.*, the potential gradient between the plates will be a straight line. Now, if we assume that electrons are emitted (with zero velocities), their presence in the space between A and B will alter the potential distribution. Owing to their presence the potential at every point in the space will be lower than if no electrons were present, and the potential distribution will be represented by ObP . The electrons in the region near A act as a screen and tend to prevent the field due to B from being felt in the region near A . At any point in space having a potential V , the kinetic energy of the electrons will be

$$\frac{1}{2}mv^2 = Ve \quad (60)$$

The passage of these electrons constitutes a current. If i is the current density, the space charge is

$$\rho = \frac{i}{v} \quad (61)$$

According to Poisson's equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = -4\pi\rho \quad (62)$$

Since the plates are equipotential surfaces,

$$\frac{\partial^2 V}{\partial y^2} = 0, \frac{\partial^2 V}{\partial z^2} = 0$$

In the case of electrons, ρ is negative. Accordingly,

$$\frac{d^2V}{dx^2} = 4\pi\rho \quad (63)$$

By eliminating v between Eqs. (60) and (61) and substituting in Eq. (63), we obtain

$$\frac{d^2V}{dx^2} = \frac{4\pi i}{\sqrt{2Ve/m}}$$

which on integration gives

$$\left(\frac{dV}{dx}\right)^2 = E_0^2 + 8\pi i \sqrt{\frac{2mV}{e}} \quad (64)^*$$

E_0 the integration constant is equal to the field intensity at the surface of the cathode. For the case where I is zero,

$$\frac{dV}{dx} = E_0$$

and the potential distribution will be linear as observed above. As i is increased by increasing the filament temperature, dV/dx must increase near the anode and consequently decrease near the cathode, and the potential distribution must take a form such as ObP . As i becomes larger still, a condition is reached where E_0 becomes equal to zero. When this condition is reached, since the field at the cathode is 0, no more electrons can get away. The current under these conditions cannot be increased by

$$* \text{To integrate} \quad \frac{d^2V}{dx^2} = 2\pi\sqrt{2}\sqrt{\frac{m}{e}} \frac{i}{\sqrt{V}}$$

Multiply by $2\frac{dV}{dx}$:

$$\frac{d^2V}{dx^2} 2\frac{dV}{dx} = 2\pi\sqrt{2}\sqrt{\frac{m}{e}} \frac{i}{\sqrt{V}} 2\frac{dV}{dx}$$

any increase in filament emission. The current is now limited not by emission but by space charge. Substituting $E_0 = 0$ in Eq. (64) and integrating, we obtain

$$i = \frac{\sqrt{2}}{9\pi} \sqrt{\frac{e}{m}} \frac{V^{3/2}}{x^2} \quad (65)$$

This is the expression for the maximum current which can flow between parallel planes in a high vacuum. Actually, of course, electrons are not emitted with zero velocities but with small initial velocities. If these are taken into account, Eq. (65) is slightly modified. For most practical purposes, however, it can be used as it stands.

The effect of the initial velocities may be seen from the following considerations. Let us assume that all the electrons are given off with the same small initial velocities and that the current is limited by space charge. Then the cathode is actually giving off more electrons than can reach the anode, and accordingly some of these electrons must return to the cathode. This can occur only if there is a potential minimum close to the cathode from which electrons are moving in opposite directions. This plane then acts as a virtual cathode and Eq. (65) is still valid when all values are measured from it instead of from the cathode. In practice, of course, electrons are not emitted all with the same velocity but with a Maxwellian distribution of velocities which results in further modification of Eq. (65). For all practical purposes, however, the simple form is satisfactory.

From this equation we see that the maximum current which can pass between two parallel planes in a high vacuum is inversely proportional to the square of the distance between them and directly proportional to the $3/2$ power of the voltage. For this reason this is often referred to as the $3/2$ power law.

Infinite parallel planes never occur in practice. If we are dealing with the case of concentric cylinders, this equation becomes

$$i = \frac{2\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{V^{\frac{3}{2}}}{r\beta^2} \quad (66)$$

where r is the radius of the anode and β varies from 0 to 1 and increases with increasing values of r/a (a = radius of filament). Where r/a is greater than 10, as is usually the case in practice, β may be taken as 1. In practical units then

$$i = 14.65 \times 10^{-6} \frac{V^{\frac{3}{2}}}{r} \quad (67)$$

amp. per unit length of electrode. This is the case most commonly found.

64. Application to the Diode.

From this equation it is evident that for a given voltage the maximum current which can be drawn from a small wire filament inside a cylindrical anode is inversely proportional to the diameter of the anode. Regardless of the shape of the electrodes the maximum current always varies with the $\frac{3}{2}$ power of the voltage. In a given tube, if it is desired to double the current, it is necessary to increase the voltage by a factor of $2^{\frac{2}{3}}$ or 2.8.

If we plot the relation between anode current and voltage, the curve will follow a $\frac{3}{2}$ power law up to s , as shown in Fig. 29. Up to this point the current is limited by space charge. When the voltage is high enough so that the anode collects all of the electrons emitted by the cathode, any further increase in voltage cannot produce any further change in current and the curve becomes

*For the derivation of the equation for the case of coaxial cylinders see Appendix C.

practically parallel to the V axis. The point of inflection is called the *saturation point*. If the electrons were all emitted with zero velocity and if the cathode was a unipotential surface, the transition from the $\frac{3}{2}$ power, or space-charge limited portion of the curve, to the saturation portion would be an abrupt one. Owing to the fact that the electrons have different small initial velocities, the value of V is not the same for all electrons. Likewise, due to the iR drop along the filament, when

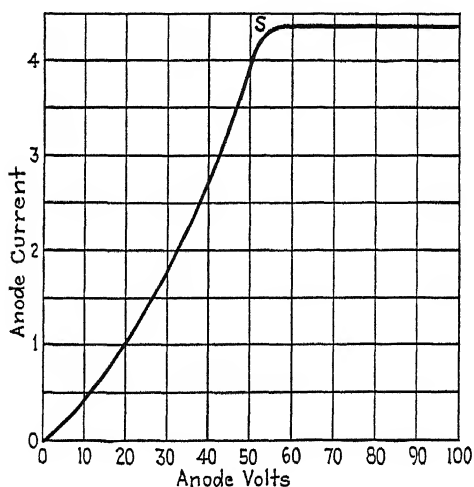


FIG. 29.—Volt-ampere characteristic illustrating the $\frac{3}{2}$ power law and the saturation point.

the saturation point is reached for the negative end, the potential difference between the positive end and the anode is less than the saturation voltage. Accordingly, instead of a sharp break, there is a gradual transition.

In practice there is a deviation from the theoretical $\frac{3}{2}$ power curve at very low voltages. The electrons are actually emitted from the filament with small initial velocities, so that the current is only reduced to 0 by applying a small negative or retarding potential. As this potential is reduced, the faster moving electrons can reach the anode so that there is actually a small current to the anode even at negative voltages, and at small

positive voltages the current is slightly larger than would be predicted from the theoretical curve.

A consequence of the space-charge limitation of current is that, provided the filament is emitting enough electrons to carry the current indicated by Eq. (66), the current is not affected by any changes in thermionic emission. The current is determined solely by the anode voltage. If more electrons are emitted than can be drawn over to the anode, they are simply returned to the filament.

65. The $\frac{3}{2}$ Power Law for Positive Ions.

The same $\frac{3}{2}$ power law applies to currents carried by positive ions. In this case \sqrt{m} , which occurs in the denominator of Eq. (66), is the mass of the positive ion instead of the mass of the electron. \sqrt{m} for mercury would therefore be 607 times as large as for electrons. This means that the maximum current which could be carried by mercury ions would be only $\frac{1}{607}$ of that which could be carried by electrons in the same tube under the same voltage conditions. For caesium the ratio would be 1:494. Or, conversely, in order to pass the same current the $\frac{3}{2}$ powers of the voltages would have to be 607 and 506 times as large for mercury and caesium ions, respectively, as for electrons.

66. Effect of Positive Ions on an Electron Discharge.

This $\frac{3}{2}$ power law is followed only in a discharge where the carriers are all of one sign, *i.e.*, all electrons or all positive ions. It serves as a very sensitive test of the degree of vacuum in an electron discharge tube. Any deviation from the $\frac{3}{2}$ power law indicates the presence of positive ions and therefore of gas. The law can be tested most conveniently by plotting the $\log i$ against $\log V$, for, if we take the logarithm of both sides of Eq. (66), we obtain

$$\log i = \log C + \frac{3}{2} \log V \quad (68)$$

Accordingly, a plot of $\log i$ against $\log V$ should give a straight line having a slope of $\frac{3}{2}$.

The presence of positive ions in the discharge tends to neutralize the space charge due to the electrons and so permit a larger current to flow than would be possible under the same conditions in a pure electron discharge. The positive ions are relatively massive and slow moving, and remain in the field a long time and so neutralize the charge of a large number of electrons. For example, a mercury ion has 366,000 times the mass of an electron. The relative velocities of electrons and mercury ions having the same kinetic energy will be in the ratio of the square roots of the masses or 1:607. Accordingly, a mercury ion will remain in the field 607 times as long as an electron. Langmuir has shown that for each positive ion (in this case assumed to be generated at the anode) of mercury, argon and hydrogen in a discharge the increase in the number of electrons that cross the space will be 229, 102 and 23, respectively. Thus the current carried by the positive ions themselves is quite negligible compared with the increase in the electron current which they produce. A small amount of gas or vapor in a tube may in consequence greatly affect the current passing through the tube. This is not due to the current carried by the positive ions themselves, since the $\frac{3}{2}$ power law shows that this can be only a small fraction of the electron current, but due to the effect of the positive ions on the field.

The effect of a small amount of gas upon the volt-ampere characteristic of an electron discharge tube is shown in Fig. 30. The full curve is the relation between current and voltage in this tube when no gas is present. This curve follows the $\frac{3}{2}$ power law until saturation is reached. If a little gas is present in the tube, it does not

produce any marked effect until the anode voltage is somewhat in excess of the ionizing voltage. As soon as this value is exceeded and ions are produced, they tend to neutralize space charge so that the current which flows is greater than that which could flow at the same voltage in the absence of ions. Thus the characteristic when gas is present is steeper and lies above the vacuum

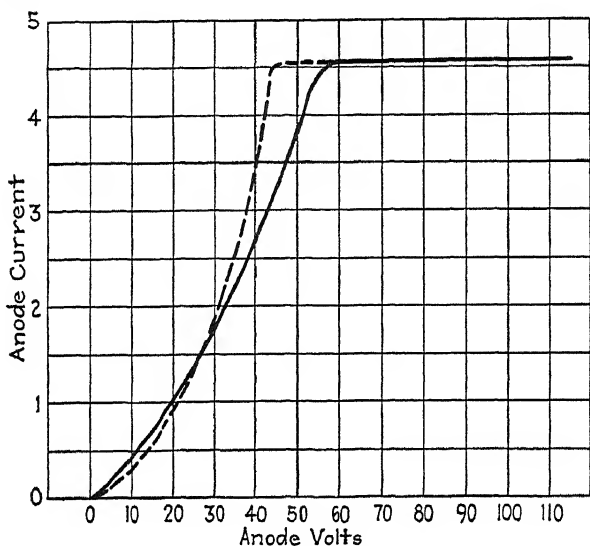


FIG. 30.—The effect of a small quantity of gas upon the space-charge characteristic.

characteristic. It is represented by the dotted line in Fig. 30. If the amount of gas present is small, the current carried by the ions is negligible, so that the magnitude of the saturation current is practically the same as for the high-vacuum condition. Saturation is reached, however, at a lower voltage.

67. Transition Region.

A number of factors operate to modify the $\frac{3}{2}$ power law. One of these is the non-uniformity of temperature over the surface of the cathode. For example, in the case of a filament the ends are cooler, owing to the lead losses, than the center portion so that the thermionic

current is less from the ends than from the center. Accordingly, saturation is reached for the ends at a lower anode voltage than for the middle. A given voltage might be above the saturation for the ends of the filament and on the space-charge portion of the characteristic with respect to the middle.

In the case of a filament with an iR drop, large compared with the anode voltage, the $\frac{3}{2}$ power law must be modified. The law still holds for each small portion of the filament, but, when the anode voltage is equal to or less than the iR drop across the filament,

$$i = kV^{5/2} \quad (69)$$

Thus, at low anode voltage, the $\frac{3}{2}$ power law is replaced by a $\frac{5}{2}$ power law.

68. Volt-ampere Characteristic.

The volt-ampere characteristic of any electron discharge tube may be considered as consisting of three parts:

1. Current determined by the initial velocity of the electrons.
2. Current determined by space charge.
3. Current determined by filament emission.

Since electrons have small initial velocities, they are capable of moving against a retarding field. If the mean kinetic energy of the electrons is kT , this can be converted into equivalent volts by the relation

$$Ve = kT \quad (70)$$

According to the Boltzmann equation the fraction of the emitted electrons which can move against a retarding field of V volts is

$$\frac{n}{n_0} = \frac{i}{i_0} = e^{-Ve/kT} \quad (71)$$

Accordingly, for negative voltages the volt-ampere characteristic may be described by the equation

$$\log i = c - \frac{Ve}{kT} \quad (72)$$

For positive voltages this equation gives place to the $\frac{3}{2}$ power law, $i = kV^{\frac{3}{2}}$, which applies until saturation is reached. If it were not for space charge, the current

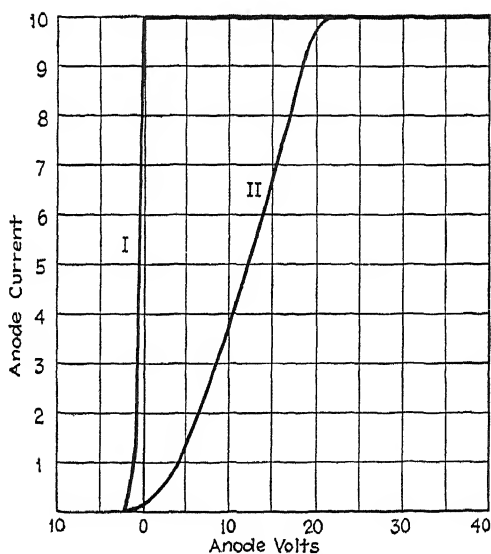


FIG. 31.—Comparison of volt-ampere characteristics in the presence and absence of space charge.

would increase according to the former relation up to zero volts. At this point saturation would take place and there would be no further increase in current with increasing voltage. The volt-ampere characteristic would be like curve I in Fig. 31. Actually space charge makes itself felt at very low values of current, so that the current follows the $\frac{3}{2}$ power relation of curve II.

69. Ionization Gage.

The ionization of gas in a three-electrode tube has been developed into a very convenient means of measuring

small pressures (ionization gage). The electrical connections are shown in Fig. 32. Electrons are accelerated between the cathode and the grid. Since the plate is at a negative potential, electrons cannot reach it. Some electrons, however, pass through the meshes of the grid and collide with gas molecules and ionize them before they finally return to the grid. The positively charged gas ions go to the plate, and the current to the plate is therefore a measure of the number of ions. The number of molecules ionized is directly proportional to the electron current to the grid over a wide range. It increases with increasing grid potential. The constant of the gage depends to some extent upon its construction and upon the nature of the gas. This type of gage has been used to measure pressures as low as 10^{-8} mm.

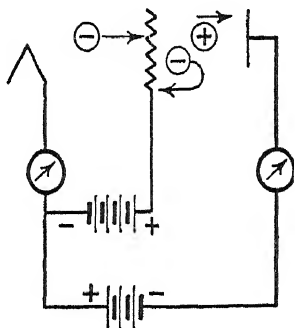


FIG. 32.—Connections for ionization gage.

70. Control of Electron Currents by a Grid.

The addition of a grid between the anode and cathode of a two-electrode tube makes it possible to control a large plate current by means of a very small potential applied to the grid. When a grid is interposed between the plate and filament, the field near the filament is altered. It is now due to two components: the field produced by the grid itself and the stray field of the plate which acts through the openings of the grid. The stray field near the filament due to the plate depends upon the grid construction. If the grid mesh is very fine, naturally it practically shields the cathode from the plate; while if the grid mesh is coarse, the stray field is greater. If the anode potential is kept constant, the current to the anode is a function of the grid potential only.

The stray field due to the anode potential E_b may be expressed by

$$E_s = \gamma E_b \quad (73)$$

where γ is determined by the grid construction. The field due to the grid is E_g plus ϵ which is due to the contact difference in potential between grid and filament. The total field at the filament therefore is

$$\gamma E_b + E_g + \epsilon \quad (74)$$

It has been shown empirically that

$$I = k(\gamma E_b + E_g + \epsilon)^{3/2} \quad (75)$$

71. Gridlike Action of Bulb Walls.

The gridlike action of the walls of a vacuum tube may be quite important in some cases. The glass walls of a well-exhausted vacuum tube are good insulators, so that any electrons which reach them stay there and charge up the surface. The potential attained by the surface depends upon its insulating properties. If the anode is at some distance from the cathode, its field may be relatively weak compared with the field produced at the cathode by the negatively charged walls, and hundreds of volts may be required to pass a current between the electrodes. This effect is not observed in tubes containing gas, once the discharge has been started, for if gas is present some of the gas molecules are ionized by collision with electrons and the positive ions are attracted to the negatively charged bulb walls and discharge them. Before the gas has been ionized, however, the charging up of the walls may necessitate a very high starting voltage (in some cases several thousand volts).

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CHAPTER IX

DISCHARGES IN GASES

72. The Phenomena.

Up to this point we have considered only electron discharges where the current carried by ions has been negligible compared with that carried by electrons. In gaseous discharges the phenomena become vastly more complex. Discharges in gases assume many different forms, such as sparks, brush discharges, corona, glow discharges and arcs. These merge in a manner that makes it very difficult to distinguish them from each other, and this is particularly true in the case of glow discharges and arcs. The glow discharge differs from the arc in that in the former the electrons must be supplied by the processes of the discharge itself, *i.e.*, the discharge takes place between cold electrodes. Arcs usually involve larger currents. The most important from a practical viewpoint are the arcs. Typical examples are the mercury and neon arcs used for lighting, mercury and Tungar* rectifiers, Phanatrons and Thyratrons.*

The voltage at which a gaseous discharge starts between cold electrodes is known as the *breakdown voltage*. The experimental determination of this voltage is beset with many difficulties. It depends not only upon the nature and pressure of the gas in which the discharge takes place but also upon the chemical nature and geometrical configuration of the electrodes, as well as of the walls of the discharge tube. In pure gases the break-

* Tungar and Thyatron are trade-marks of the General Electric Co.

down voltage passes through a minimum with increasing gas pressure. The shape of the curve, as well as the value of the minimum, depends upon the nature of the gas. The curves for hydrogen, argon and neon are shown in Fig. 33. The effect of impurities entirely alters the

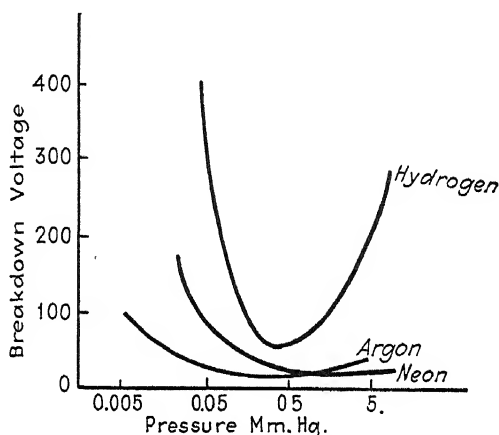


FIG. 33.—Breakdown voltage as a function of pressure in hydrogen, argon, and neon. (*Alterthum, Reger and Seeliger.*)

relation between breakdown voltage and pressure, and no general relation can be stated for mixtures.

A description of the appearance of a typical glow discharge will be of some assistance in understanding the processes taking place in it, as the visible structure

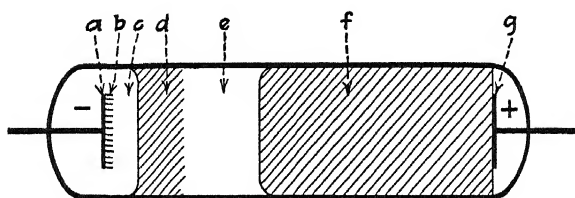


FIG. 34.—Appearance of a glow discharge between cold electrodes. *a*, cathode; *b*, cathode glow; *c*, negative dark space; *d*, negative glow; *e*, Faraday dark space; *f*, positive column; *g*, anode.

indicates points in the discharge which are differentiated from the cathode by marked potential differences. Let us start with a tube, such as shown in Fig. 34, with two cold electrodes and an applied potential of a few hundred volts. At atmospheric pressure no discharge takes place.

As the pressure is decreased, first streamers pass between the electrodes and then gradually the discharge changes to a glow filling the whole tube. This uniform glow is called the *positive column*. As the pressure is lowered still more, a dark space, called the *Faraday dark space*, appears between the end of the positive column and the cathode. The cathode is surrounded by a glow called the *negative glow*. As the pressure is lowered still further, the Faraday dark space and the negative glow move away from the cathode and another dark space, called the *cathode dark space*, appears between the negative glow and the cathode. The cathode is now surrounded by the cathode glow. The positive column may be continuous or may be broken up by transverse striations.

At any given pressure the negative glow and the Faraday dark space appear to be fixed with reference to the cathode. If the anode is moved toward the cathode, the positive column becomes shorter while the other portions of the discharge remain unchanged. Thus, if the anode is moved close enough to the cathode, the positive column may disappear entirely and the anode may be moved into the cathode dark space. Figure 35*a*, *b* and *c* shows the structure of a glow discharge for three different positions of the anode, all other conditions remaining unchanged. In *a*, the discharge shows a long positive column. In *b*, where the anode has been moved closer to the cathode, the positive column has been shortened by just the amount by which the anode has been displaced. In *c*, the anode has been moved up into the Faraday dark space and the positive column has entirely disappeared. Similarly, at very low pressures, the cathode dark space expands (at the expense of the positive column) until it reaches the anode. This discharge is the type studied by Crookes. In most of the discharges used for lighting, the pressure is sufficiently high so that the positive column, which is the

most luminous part of the discharge, fills practically the entire tube and the cathode, and Faraday dark spaces move so close to the cathode that they become indistinguishable. The dark space is not actually dark but only appears so by contrast with the more luminous portions of the discharge.

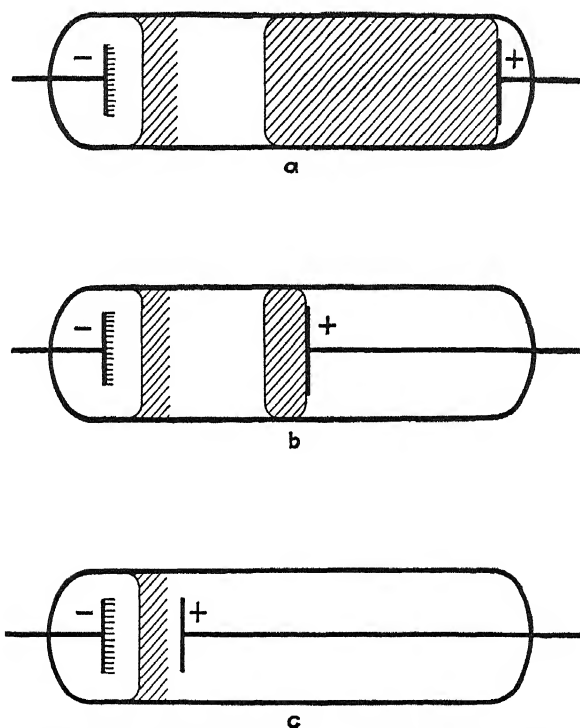


FIG. 35.—Effect of the position of the anode on the positive column of a glow discharge.

When the current through the tube is small, the cathode glow occupies only a small portion of the cathode area. As the current is increased, the area of the glow increases until it covers the entire cathode, *i.e.*, the current density at the cathode remains constant until the glow covers the entire surface.

73. Potential Distribution and Cathode Fall.

The potential distribution in the tube is shown in Fig. 36. The drop in the positive column is relatively

small. There may be a slight rise in potential through the negative glow. Most of the drop in potential takes place between the negative glow and the cathode. The drop between the cathode and the negative glow is called the *cathode fall*. It is independent of current until the current is large enough so that the glow covers the entire cathode surface. This normal cathode fall is a charac-

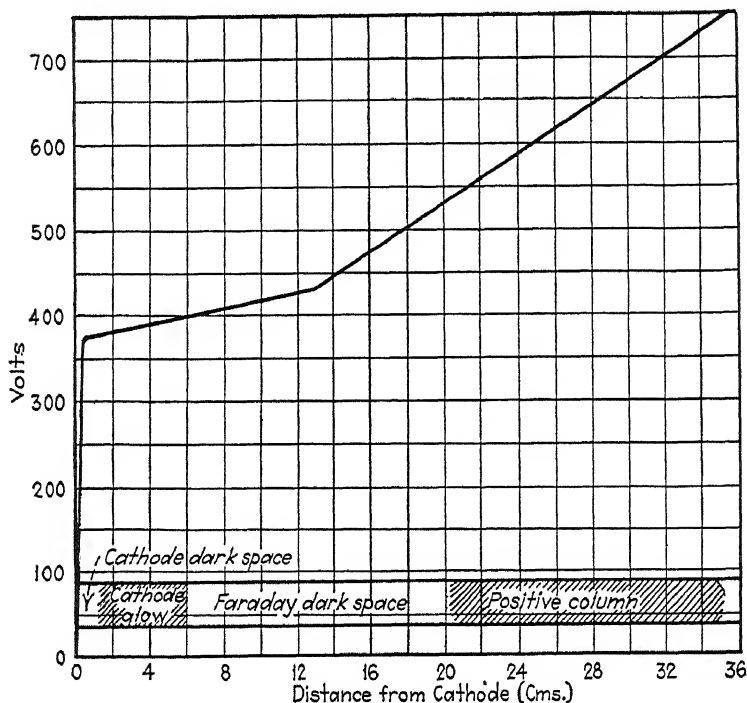


FIG. 36.—Potential distribution in a glow discharge. (Found and Forney, *Trans. Am. Inst. Elec. Eng.*, 47, 4, 1928.)

teristic of the gas in which the discharge takes place and of the material used for the cathode. Values of cathode fall for some of the more common gases and electrode materials are given in Table VIII. The cathode fall is greatly altered by the admixture of even a trace of a foreign gas. From Table VIII it can be seen that the cathode fall is lowest for the rare gases and for electrodes of the alkali and alkali-earth metal group. In the case of the rare gases it is independent of pressure. In

hydrogen and nitrogen, however, it increases with decreasing gas pressure. If the current is increased beyond the point where the cathode glow covers the entire cathode, the cathode fall increases. This region is known as the *region of the abnormal cathode fall*.

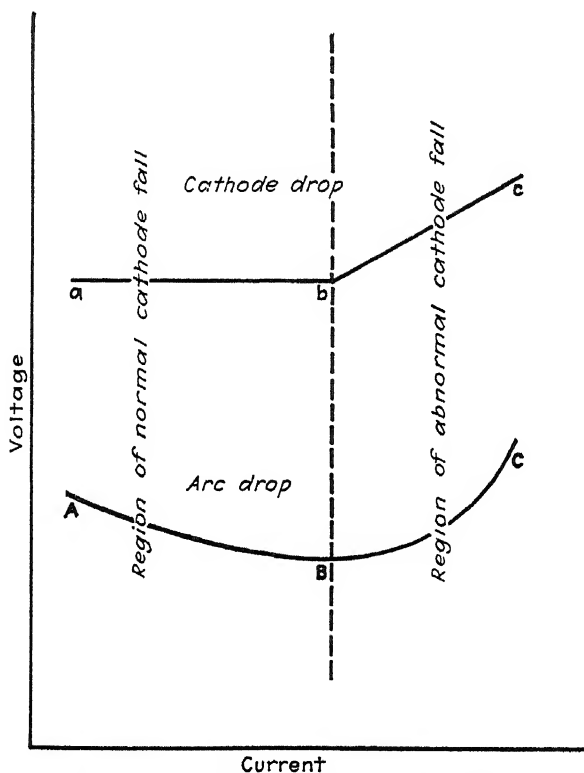


FIG. 37.—Relation between the volt-ampere characteristic of a discharge and the cathode fall.

The volt-ampere characteristic of a glow discharge is intimately related to the cathode fall. For values of current for which the cathode fall is normal, as in the region *ab*, Fig. 37, the discharge has a negative volt-ampere characteristic, as in the region *AB*. This negative characteristic is really the characteristic of the positive column. When the glow covers the entire cathode, the voltage passes through a minimum, and beyond this point the slope of the volt-ampere charac-

teristic BC is positive. This is because of the rapid increase in the abnormal cathode fall bc with increasing current, which more than compensates for the drop in voltage of the positive column.

It is the behavior of the cathode fall which is responsible for the rectifier action of certain types of glow discharges. The discharge will rectify if the electrodes A and B are chosen of such dimensions that when A is used as cathode the cathode fall is normal, while if the same current is passed through the tube in the reverse direction so that B serves as cathode the cathode fall is abnormal. When the discharge is operated on alternating current, more current will flow from B to A than in the reverse direction. This condition is attained when A has a large and B a small surface such as a plate and a point, respectively. Similar effects are obtained by various other asymmetrical types of electrodes. For example, as will be discussed later, the cathode fall is very low when a heated thermionic emitter serves as cathode. In this case a large arc current will flow through the tube in one direction, while in the other direction there will simply be the small current characteristic of a glow discharge between cold electrodes (or no current at all if the voltage is below the breakdown voltage).

The characteristics of a glow discharge or an arc depend largely upon the pressure of the gas present. In the case of permanent gases this is determined by the ordinary gas laws. In the case of vapors it is determined by the temperature of the liquid. The mere fact that gas is present is not sufficient in itself to change the nature of a pure electron discharge. The significant fact is that positive ions are present and are continually being formed from the neutral gas molecules and disappearing again by recombination.

74. Ionization by Electron Impact.

Several processes are at work forming ions in a gaseous discharge. The most important of these is ionization by electron impact. A collision between a fast-moving electron and a gas molecule may result in knocking an electron completely out of its orbit in the molecule and so leaving the latter ionized. The amount of energy necessary to remove one of the outer electrons from its orbit is

$$\Delta W = h\nu \quad (76)$$

where h is the quantum constant 6.547×10^{-27} erg-sec., and ν the frequency of the radiation which the electron emits in returning to its normal orbit; or expressed in equivalent volts,

$$\Delta W = eV_i \quad (77)$$

where V_i is known as the ionizing voltage. Table IX gives values of ionizing voltages for some of the more common gases. In order to ionize a gas molecule, with which it collides, an electron must possess at least an amount of energy equivalent to the ionizing voltage. Not every collision, however, results in ionization. The probability of ionization when an electron collides with a gas molecule increases linearly with increase in energy of the impacting electron from a value of zero at the minimum ionizing potential up to about twice this energy and then more slowly. If the impacting electron has more than the amount of energy necessary for ionization, the excess may be shared in any manner by the impacting electron, the ejected electron and the ion.

The original impacting electron as well as the electrons knocked out of the molecule may collide with other molecules and produce more ions. The total number of ions produced as the result of a single primary electron

at different voltages in various gases is shown in Table X.

75. Mean Free Path.

The probability of an electron colliding with a gas molecule naturally depends upon the number of gas molecules present and their size; *i.e.*, on the pressure and nature of the gas. The average distance which a particle moves between collisions is called the *mean free path*. This is the reciprocal of the number of collisions per unit path length. For electrons moving through a gas of molecular radius σ , where there are N molecules per cubic centimeter, the mean free path can be calculated from the equation

$$\lambda = \frac{1}{\pi N \sigma^2} \quad (78)$$

Table XI gives the values of λ for electrons passing through a number of different gases. From the expression for λ it can be seen that it is inversely proportional to the number of molecules per unit volume or to the pressure.

76. Cumulative Ionization.

Ionization by a single electron impact is not the only mechanism by which ionization may take place. When a collision occurs between a molecule and an electron with less energy than the amount required for ionization, the molecule may be left in an excited condition. In this condition an outer electron has been displaced from its orbit but not completely removed from the atom. The atom returns to the normal state as the electron drops back into its proper orbit with the emission of a quantum of radiant energy. The normal life of an atom in the excited condition is of the order of 10^{-7} or 10^{-8}

sec. While the atom is in the excited state it may be struck by another electron with sufficient additional energy to complete the ionization process. It may also acquire the additional energy by the absorption of radiation of exactly the right frequency, or by collision with another excited atom. This ionization in successive stages is called *cumulative ionization*. A detailed discussion is given in Compton and Langmuir's "Electrical Discharges in Gases."

Ionization may also take place by "collisions of the second kind," in which a molecule is ionized by collision with another ionized or excited molecule. Cumulative ionization is greatly enhanced by the presence of metastable atoms. These are excited atoms having an abnormally long life in the excited state, of the order of 0.1 sec. The fact that an atom continues in the excited state for a long time naturally increases the probability of its meeting with another collision before it returns to the normal state.

Ionization by impact of positive ions and thermal ionization are relatively unimportant.

In a glow discharge, then, all of the processes enumerated above are taking place.

77. Arcs and Glow Discharges.

The dividing line between *arcs* and *glow discharges* is not always clear. In some cases it is gradual and in others abrupt. Compton has defined an arc as "a discharge of electricity, between electrodes in a gas or vapor, which has a negative or practically zero volt-ampere characteristic and a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor." The essential feature of the arc is "the emission of electrons from the cathode which produces sufficient ionization of the surrounding gas to give a positive space charge just outside of the

cathode, thus facilitating ionization and permitting a large, generally saturation, electron emission at relatively low voltages." The electrons from the cathode may be liberated simply by thermionic emission, or they may be pulled out of the cathode by the intense field in the cathode-fall space. In some arcs the thermionic emission is due to the heating of the cathode, as the result of positive-ion bombardment. In some commercial types the cathode is heated by an external source to supply the thermionic emission. Hot-cathode arcs of this type start at a low voltage as the electron emission from the cathode is sufficient to produce enough ionization to effect the low cathode drop at low voltage.

It has been shown by several investigators that in arc discharges the total current is supplied by the electron emission from the cathode. The additional current carried by the ions is very small. The essential feature of the arc is sufficient ionization in the region just outside the cathode to produce a positive-ion space charge so that the saturation electron current may be obtained at relatively low voltages.

Some types of arc discharges when once started can be maintained at voltages below even the minimum ionizing potential of the gas, provided the cathode is heated by some independent means. The supply of ions necessary to the passage of the arc current is probably kept up by combinations of the various ionization processes already discussed. These may be successive electron impacts; successive absorption of radiation; successive collisions of the second kind or combinations of these, such as electron impact and absorption of radiation; electron impact and collisions of the second kind; or absorption of radiation and collisions of the second kind. No single elementary process alone can account for the low-voltage arc. The Tungar rectifier is a typical example of a low-voltage arc of this kind.

The volt-ampere characteristic of the discharge itself must not be confused with the volt-ampere characteristic of the discharge plus the series resistance with which it is usually operated. In Fig. 38, curve aa' represents the volt-ampere characteristic of the discharge, while the straight line bb' represents the volt-ampere characteristic of the series resistance R . The arc must operate

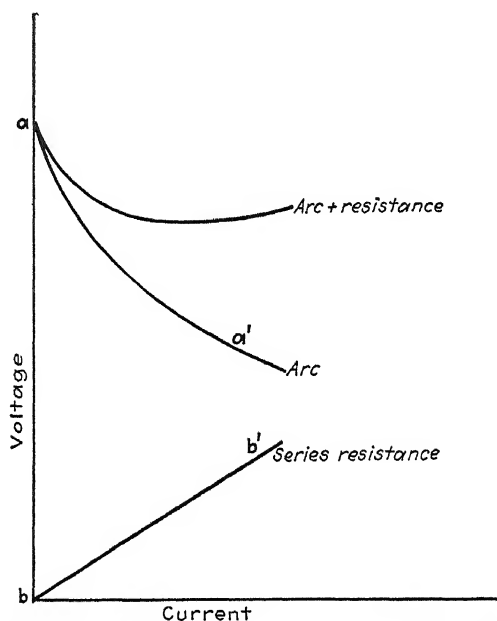


FIG. 38.—Relation between the over-all volt-ampere characteristic and that of the discharge alone.

at a current such that the sum of the two voltage drops is just equal to the supply voltage.

78. Probe Electrodes.

Much information as to the nature of gaseous discharges has been obtained from a study of the volt-ampere characteristics of auxiliary or probe electrodes placed in the path of the discharge. If an auxiliary electrode is placed in the path of a discharge, it acquires a definite potential a few volts negative with respect to the gas surrounding it. If it is maintained at a positive

potential, it will collect electrons and function as an anode in the discharge. If it is made negative, it will collect positive ions. From the volt-ampere characteristics the density of ions and electrons in the discharge can be determined.

79. Ion Sheaths.

Let us assume a plasma (a uniform region of an ionized gas in which electron and positive-ion concentrations are approximately equal) with equal numbers of ions and electrons moving in random directions. The number of electrons which will pass across an imaginary surface in a unit time will be greater than the number of ions because of the greater mobility of the electrons. For example, in the case of a discharge in mercury vapor, the random electron and ion currents (*i.e.*, the charge carried across a unit area per second) will be in the ratio of 607:1, since this is the ratio of the square roots of the masses of the particles. Thus, although there are equal numbers of ions and electrons in each unit volume of the discharge, the number of electrons crossing any unit area in the discharge, in the absence of any disturbing field, will be 607 times as great as the number of ions. If a negatively charged electrode is placed in the discharge, it will collect positive ions and repel electrons. There will thus be a region or sheath around the electrode which contains positive ions but no electrons. The space charge of the positive ions neutralizes the field of the collector so that it is not felt beyond the edge of the sheath which is at the same potential as the ionized gas. Thus, in a gaseous discharge a negatively charged electrode forms a sheath of positive ions around itself and the field of the electrode is limited by the edge of the sheath.

Similar phenomena take place about an electrode at a positive potential. In this case, however, if the potential

of the electrode is high enough, electrons in passing through the sheath may ionize by collision and so neutralize the electron space charge.

Since the field of the collector is zero at the outer edge of the sheath, the current is determined only by the number of ions which pass through the edge of the sheath as a result of their own random motions. The current to the collector then is a measure of the positive-ion current density in the discharge. This, of course, is independent of the voltage applied to the collector. We thus have a current of positive ions flowing from the edge of the sheath to the collector which is subject to the ordinary laws of space charge, and the thickness of the sheath can be calculated by the space-charge equation

$$I = \frac{\sqrt{2}}{9\pi} \sqrt{\frac{e}{m}} \frac{V^{\frac{3}{2}}}{x^2} \quad (79)$$

where m is the mass of the positive ion. Having obtained the thickness of the sheath, the current *density* across the boundary of the sheath may be obtained. Ion sheaths may readily be observed visually. The details of measurements by means of probe electrodes, and the information which may be obtained by their use, is beyond the scope of this chapter. The concept of ion sheaths, however, is important and has practical bearing on vacuum-tube operation.

The thickness of the ion sheath depends upon the voltage applied to the electrode and on the current density in the discharge. From Eq. (79) it can be seen that it is proportional to the $\frac{3}{4}$ power of the voltage and inversely proportional to the square root of the current density. In discharges where the ion density is high, therefore, the thickness of the ion sheaths is small.

* This form of the equation applies to plane electrodes only.

80. Plasma Oscillations.

It has been found that certain types of oscillations of the ions and electrons of the plasma may take place in gaseous discharges. These oscillations are characteristic of the plasma and are entirely independent of the constants of the external circuit. The discovery of such oscillations is due to the observation by Langmuir of the scattering of a stream of electrons when projected into an ionized gas. The electrons acquire a velocity distribution which cannot be explained on the basis of collisions with the gas alone. This led to a search for another mechanism which was found when Penning discovered that, in the plasma, oscillations of the electrons are taking place with frequencies as high as 1.2×10^9 and an amplitude of the order of 0.2 volt. These oscillations are observed in any part of the plasma. Their frequency is measured by means of a Lecher wire system.

The frequency has been shown to be

$$\nu = \left(\frac{ne^2}{\pi m} \right)^{1/2} = 8980n^{1/2} \quad (80)$$

where m = mass of the electron

e = electronic charge

n = number of electrons per unit volume.

Assuming an electron density of 10^{10} electrons per cubic centimeter, this would correspond to a wave length of 33.5 cm.

Oscillations of the ions of the plasma have been found by Pardue and Webb which are quite analogous to the electron oscillations but with lower frequencies owing to the larger mass involved.

81. Barkhausen-Kurz Oscillations.

Another type of oscillation, in which the frequency is controlled by the applied voltages, was discovered in

high-vacuum tubes by Barkhausen and Kurz. These oscillations may take place in a tube in a circuit such as that shown in Fig. 32 for the ionization gage, where electrons are accelerated from the cathode to the grid. Those which are not caught by the grid pass through it but are not able to reach the anode because of its negative potential. They return toward the grid, and some are caught there while others may pass between the grid wires and thus oscillate back and forth several times before finally reaching the grid. Under some conditions this may lead to sustained oscillations. Barkhausen derived the relation between the wave length and the tube dimensions as follows:

Let d_a and d_g be the diameters of the grid and anode, respectively, and let E_a and E_g be the voltage applied to the grid and anode, respectively.

Then an electron reaching the grid will have a kinetic energy

$$\frac{1}{2}mv^2 = eE_g \quad (81)$$

and

$$v = \sqrt{\frac{2e}{m}E_g} \quad (82)$$

and

$$v_{\text{aver.}} = \sqrt{\frac{1}{2} \frac{e}{m} E_g} \quad (83)$$

Owing to the negative potential applied to the anode, the electrons are unable to reach it and are stopped at a distance d' from the cathode such that the voltage against which they have traveled from the grid to d' is just equal to that applied between cathode and grid. Then

$$\frac{d' - \frac{d_g}{2}}{d_a - d_g} = \frac{E_g}{E_g - E_a} \quad (84)$$

and

$$d' = \frac{E_g d_a - E_a d_g}{2(E_g - E_a)} \quad (85)$$

The distance traversed in one complete oscillation is $2d'$ and the frequency

$$n = \frac{\sqrt{\frac{1}{2} \frac{e}{m} E_g}}{\frac{E_g d_a - E_a d_g}{E_g - E_a}} \quad (86)$$

The wave length of the radiation is

$$\begin{aligned} \lambda &= \frac{3 \times 10^{10}}{n} = \frac{E_g d_a - E_a d_g}{E_g - E_a} \sqrt{\frac{2m}{E e_g}} \times 3 \times 10^{10} \\ &= \frac{1000}{\sqrt{E_g}} \frac{d_a E_g - d_g E_a}{E_g - E_a} \end{aligned} \quad (87)$$

This equation does not take into account the effects produced by space charge.

TABLE VIII.*—CATHODE FALL IN VOLTS FOR VARIOUS GASES AND ELECTRODE MATERIALS

Electrode material	Oxygen	Hydrogen	Nitrogen	Helium	Neon	Argon
Sodium .....	.	185	178	80	75	
Gold .....	.	247	233			
Magnesium.....	310	153	188	125	94	119
Mercury .....	..	270	226	142.5		
Aluminum.....	311	171	179	141	120	100
Tungsten.....	..	.	..	..	125	
Iron	343	198	215	161	..	131
Nickel .....	..	211	197	...	..	131
Platinum.....	364	276	216	160	152	131

* "Handbuch der Experimentalphysik," vol. XIII, Pt. III, p. 350

TABLE IX.¹—IONIZING VOLTAGES FOR VARIOUS GASES

Gas	Ionizing Voltage
Argon	15.4
Neon	21.5
Helium	24.6
Hydrogen	29.4
Nitrogen	16.7
Oxygen	23.9
Carbon monoxide	14.2
Mercury	10.4
Water	13.2

* "International Critical Tables," McGraw-Hill Book Company, Inc., New York, 1929.

TABLE X.*—TOTAL NUMBER OF IONS PRODUCED BY SINGLE ELECTRON AT VARIOUS VOLTAGES

Gas	V = 30	V = 50	V = 75	V = 100
Helium . . . . .	.. .	1 2	...	2 9
Neon . . . . .	..		1 2	2 0
Argon	0 45	0 9	.	1 6
Hydrogen . . . . .		.	..	1 4
Nitrogen . . . . .	.		1 3	1.6
Mercury	1 1	1 4		2 7

* LANGMUIR and JONES, *Phys. Rev.*, **31**, 402, 1928.

TABLE XI.*—MEAN FREE PATH OF ELECTRONS IN VARIOUS GASES

Gas	λ = Mean Free Path in Centimeters (at Pressure of 1 Mm.)
Mercury	0.0149
Argon	0.0450
Neon	0.0787
Helium	0.1259
Hydrogen	0.0817
Nitrogen	0.0425
Oxygen	0.0455

* COMPTON and LANGMUIR, *Rev. Mod. Phys.*, **2**, 208, 1930.

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WIEN-HARMS: "Handbuch der Experimentalphysik," vol. XIII, Pt. III.

CHAPTER X

GRID-CONTROLLED ARCS

82. Effect of a Grid in a Gaseous Discharge.

The control of an arc by means of a grid is of considerable practical importance. Gaseous discharge tubes employing this kind of control are manufactured by the General Electric Company under the trade name Thyratrons. Owing to the presence of ionized gases, their characteristics are radically different from those of three-electrode high-vacuum tubes.

A grid placed between cathode and anode of a hot cathode tube, containing gas, if sufficiently negative, will prevent the arc from striking because under these conditions there is no accelerating field around the cathode. The electrons therefore cannot acquire sufficient velocity to ionize. When the grid is made positive, the electrons are accelerated toward it. They collide with gas atoms, ionizing them, and the arc strikes. Thus a negative grid prevents the arc from striking and a positive grid allows it to strike.

After the arc has struck, it presents the peculiar feature that the grid has no more control over it. The current to the anode is quite independent of the potential of the grid, and the arc cannot be stopped by applying any practical negative voltage to the grid. The explanation of this behavior lies in the properties of positive-ion sheaths, which were discussed in the previous chapter. When the arc strikes, the region between the electrodes becomes a plasma with ions and electrons present in equal numbers. If a negative potential is

applied to the grid, a sheath of positive ions is formed around the grid wires. The outer edge of this sheath is at the same potential as the plasma regardless of the applied grid potential, for the potential of an electrode in a plasma cannot make itself felt beyond the edge of the sheath. The only effect of varying the potential of an electrode within a sheath is to increase the thickness of the sheath. Once the arc has struck, therefore, and the grid wires

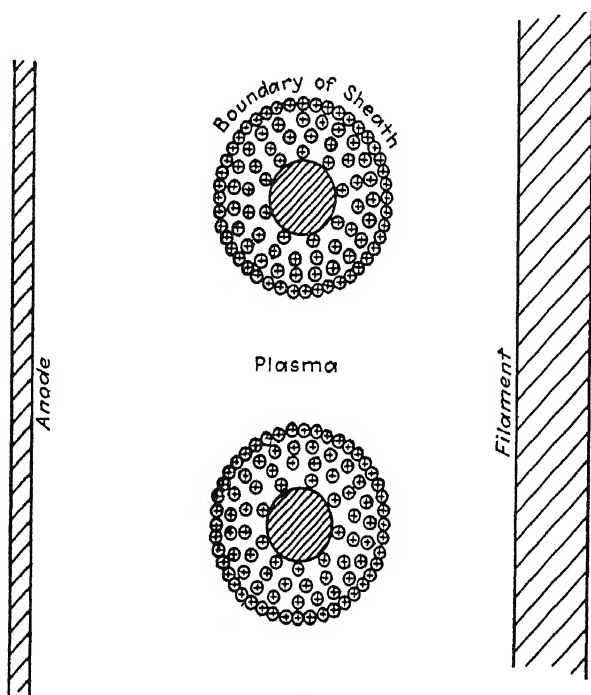


FIG. 39.—Vicinity of a negatively charged grid wire in a plasma, showing positive-ion sheaths. (Hull and Langmuir, *Proc. Nat. Acad. Sci.*, **51**, 219, 1929.)

have become surrounded by a sheath, the grid potential cannot be felt beyond the boundary of this sheath for moderate grid voltages. Increasing the grid potential has only the effect of extending this boundary. The conditions in the vicinity of a negatively charged grid can be seen from Fig. 39. The plasma in which the grid is immersed remains quite undisturbed in the region between neighboring sheaths. Unless the sheaths over-

lap, the grid has practically no effect on the plasma and so cannot stop the arc. At high values of current density the sheaths are very thin and cannot be made to overlap, except at very high values of voltage. For example, in the case of an arc in mercury vapor, the thickness of the sheath around a grid wire 0.02 cm. in diameter at a negative potential of 6 volts is about 0.0012 cm. The thickness of the sheath increases with the $\frac{3}{4}$ power of the negative grid voltage. Accordingly, it would require an extremely high voltage to cause overlapping of the sheaths and stopping of the arc.

83. Grid-control Ratio.

After the arc has started, varying the grid potential does not cause any corresponding variation in the anode current, as in the case of a high-vacuum tube. Accordingly, once the arc has struck, there is nothing equivalent to the amplification factor of a high-vacuum tube. The *starting* of the arc, however, is determined by the *grid-control ratio*. This is the ratio of the anode voltage to the grid voltage at which the arc will just strike. A typical grid-control characteristic is shown in Fig. 40. This is somewhat analogous to the amplification factor in a high-vacuum tube. After the arc has struck, however, the analogy ceases, for the grid no longer affects the discharge. Since the arc cannot be stopped by making the grid potential negative by any moderate amount, the only way to extinguish it is to remove the anode potential. The ions diffuse rapidly to the walls and electrodes, the ion sheaths disappear and the grid is again able to control the discharge.

84. Operation of Grid-controlled Arcs.

From this discussion it is evident that the Thyatron is able to act as a relay whereby a small amount of energy in the grid circuit is able to release a large current

in the anode circuit. The anode current, however, is not a continuous function of the grid voltage. If the arc starts at all, the anode current is limited only by the load resistance and the emission from the cathode.

The maximum current which can safely pass through the tube is limited by the saturation emission from the cathode. If the voltage impressed upon the tube is in excess of the value required to draw the saturation current, the cathode drop will rise and the cathode will be

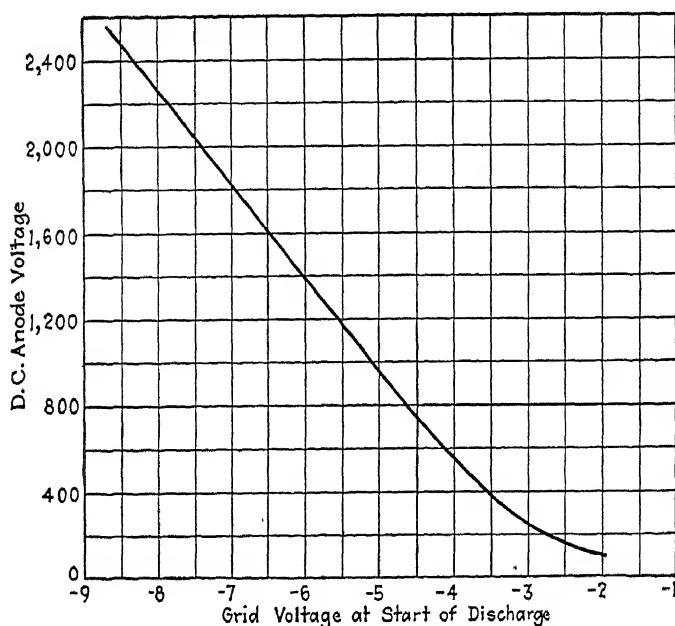


FIG. 40.—Thyratron grid-control characteristic.

bombarded by high-velocity positive ions. The harmful effects of this sputtering action have been discussed in Chap. VII. Sputtering of the cathode also takes place in Thyratrons (and other types of hot-cathode tubes) when the anode voltage is applied before the cathode has had time to attain its operating temperature. This is because the applied anode voltage is higher than is necessary to draw the saturation current from the partially heated cathode.

In practice, in place of stopping the arc by opening the anode circuit the anode is operated on alternating current. This brings the anode to zero potential at the end of each half cycle. The arc then goes out and gives the grid an opportunity to regain control. At the beginning of the next cycle it strikes again or not, according to the grid potential.

85. Deionization.

The ability of the grid to regain control in the interval of half a cycle is dependent on the removal of the positive ions of the plasma and consequently of the positive-ion sheaths in that time. For a typical grid structure the time required for the ions to disappear, or the deionization time, was found to obey the empirical equation

$$t = \frac{0.0012 p I^{0.7}}{e_g^{3/2} x} \text{ sec.} \quad (88)$$

where p = pressure in baryes

I = arc current

x = distance between grid and anode

e_g = grid potential with respect to the surrounding space.

For example, a grid 1 cm. from the anode at a negative potential of 2 volts with an arc current of 2 amp. in mercury vapor at a pressure of 5 baryes would have a deionization time

$$t = \frac{0.0012 \times 5 \times 2^{0.7}}{2^{3/2} \times 1} = 3.48 \times 10^{-3} \text{ sec.}$$

A tube of this type operating under these conditions therefore could not be operated at any frequency greater than 143 cycles per second. Any higher frequency than this would not give sufficient time in the period of half a cycle for deionization to take place and the grid would have no control. At 60 cycles, deionization does not

present any difficulties although it may at higher frequencies.

86. Control by Grid Voltage.

The operation of Thyratrons consists in "periodically stopping the discharge by removing the anode voltage and controlling its restarting by the grid." Thus the Thyatron may be started at the beginning of each cycle, in which case its output will be a maximum; or it may be started at some later portion of the cycle, in which

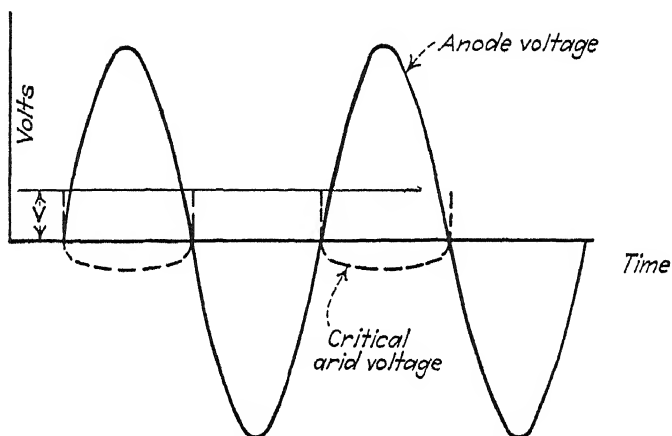


FIG. 41.—Grid-voltage control of Thyatron.

case its output will depend upon the length of time remaining till the end of the cycle.

The first type of control is illustrated in Fig. 41. The heavy curve represents the anode voltage. The dotted curve represents the critical grid voltage, *i.e.*, the grid voltage at which the tube will just start. The tube will start whenever the grid voltage exceeds this critical value and will stay on for the remainder of the cycle. As long as the grid potential is equal to, or greater than, the value corresponding to V , the tube will start at the beginning of each cycle and stay on for the entire cycle. Under these conditions the plate current will be at its maximum.

87. Control by Phase Shift.

In the second type of control, called the *phase-shift control*, the grid potential may be supplied by an alternating voltage. Four cases of this type of control are

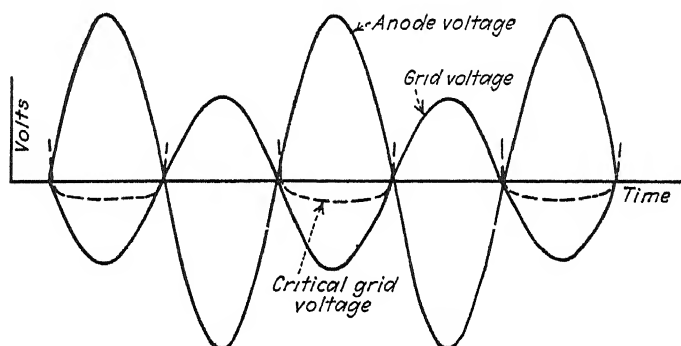


FIG. 42a.—Phase-shift method of Thyatron control. Grid voltage 180 deg. out of phase with anode voltage. Tube can never start.

shown in Fig. 42. In case (a), the grid voltage is at all times 180 deg. out of phase with the anode voltage, so that during the half cycle when the anode voltage is positive, the grid voltage is negative and the arc can

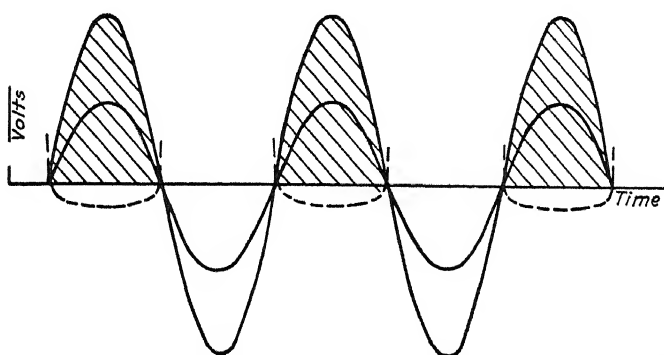


FIG. 42b.—Grid voltage in phase with anode voltage. Tube starts at beginning of each cycle and stays on for the entire cycle.

never strike. In case (b), the grid and anode voltages are in phase, so that the tube starts at the beginning of each cycle and stays on for the entire cycle. In case (c), the phase of the grid has been advanced 90 deg. The arc starts at the beginning of each positive half cycle of

anode voltage and stays on till the end of the cycle even though the grid becomes negative, because the grid has no more control after the arc has struck. In case (d), the phase of the grid potential has been retarded 90 deg.

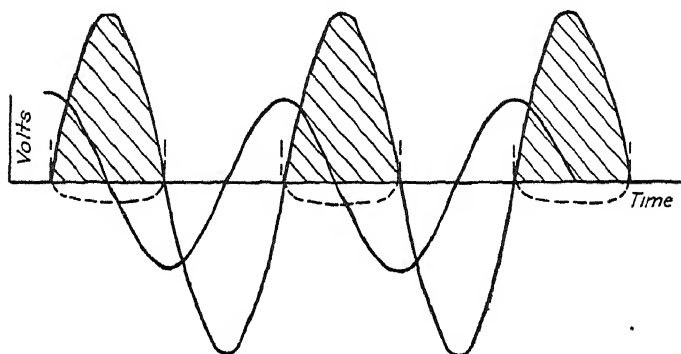


FIG. 42c.—Grid voltage 90 deg. in advance of anode voltage. Tube starts at beginning of each cycle and stays on for the entire cycle.

In this case the arc does not strike until the middle of the positive half cycle of anode voltage and remains on for the rest of the cycle. Thus, by shifting the phase of the grid, a very delicate control of the starting of the

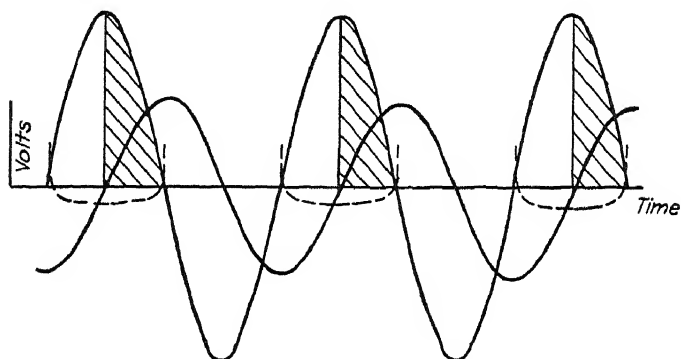


FIG. 42d.—Grid voltage 90 deg. behind anode voltage. Tube starts at middle of each cycle and stays on for remainder of cycle.

arc can be obtained. If in the initial condition the grid and anode voltages are 180 deg. out of phase, a very slight advance of the phase of the grid will turn on the arc for a fraction of the cycle which is a function of the amount of the phase shift. Varying the portion of

the cycle for which the grid is turned on, of course, varies the average current through the tube. The phase shift may be produced by variations in the resistance, inductance or capacity of the grid circuit. A circuit for controlling a Thyatron by phase shift is shown in Fig. 43. The phase-shifting device may be either a variable resistance, inductance or capacity. This method of control is very useful for photoelectric-tube applications,

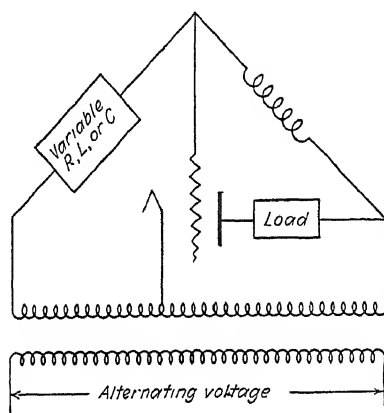


FIG. 43.—Circuit for controlling Thyatron by phase-shift method.

as such a tube may be considered a resistance whose magnitude is a function of the illumination.

88. Grid Emission.

One very important limitation in Thyatrons is that the grid must not emit electrons. Electron emission from the grid is facilitated by the deposition of active material from the cathode on the grid due to either evaporation or sputtering. If the grid is maintained at a sufficiently high temperature by radiation from the cathode, it may emit an appreciable thermionic electron current. These electrons would be drawn to the anode regardless of the grid potential and cause the arc to start even with negative grid voltages. Grid emission is avoided by constructing the grid with a large enough radiating surface to prevent its attaining a temperature

at which thermionic emission would be appreciable. The effect is also minimized by treating the grid surface in such a manner as to make it a poor thermionic emitter.

89. Gas-pressure Limits.

The upper limit of the gas pressure which may be used in Thyratrons is ordinarily determined by two factors. One of these is the rate of diffusion of positive ions. If the pressure is too high, the positive ions are prevented from diffusing to the walls and electrodes in the time of the one half cycle that the anode potential is negative. The other factor is the breakdown voltage. The gas pressure must always be low enough so that a discharge will not start between the grid and anode during the inverse half cycle. If the pressure is too low, on the other hand, the current density is so low that the ion sheaths are very large. This results in making the arc path narrow, so that the arc may be reduced or extinguished by making the grid sufficiently negative. This type of control is similar to that in a high-vacuum discharge. In the case of a vapor such as mercury, the pressure depends upon the bulb temperature which is a function of the input to the tube and the surroundings. For gases such as argon, the pressure is practically independent of temperature. Since all of the characteristics of Thyratrons are functions of pressure, the bulb temperature of mercury-vapor tubes must be kept within fairly narrow limits.

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CHAPTER XI

PHOTOELECTRICITY

90. History.

The liberation of electrons from matter under the influence of light is known as the *photoelectric effect*. The vacuum tubes designed to utilize this effect, photoelectric tubes, are becoming increasingly important in industrial applications. The photoelectric effect was discovered only a few years after Elster and Geitel's systematic investigation of thermionic emission. Much has been learned about it in recent years, but the great advance in practical applications has been due to the development of the thermionic amplifier. Without the latter the photoelectric effect would be interesting only from the laboratory and academic point of view. With the possibility of amplifying its minute currents the photoelectric tube has become a control device of considerable commercial importance. The discovery of the photoelectric effect was, like many other scientific discoveries, accidental. Heinrich Hertz was engaged in the experimental verification of Clerk Maxwell's electromagnetic theory of light. He found that sparks jumped across the gap, which he was using as a detector of electromagnetic radiation, far more readily when it was illuminated by ultraviolet radiation than when it was not. He did not investigate the effect further himself, but his discovery of the fact aroused the interest of another German, Hallwachs, who studied it in greater detail. Hallwachs worked with a zinc plate in air. He measured the rate of leak of charge (by means of an elec-

trometer) when it was illuminated by the light of an arc which was first allowed to pass through filters of different materials. He found that the light had no effect on a positive charge but that it caused a negative one to leak off. In our present terminology we describe this by saying that light causes the emission of electrons. Much experimental investigation was necessary, however, before it was definitely established that the charges

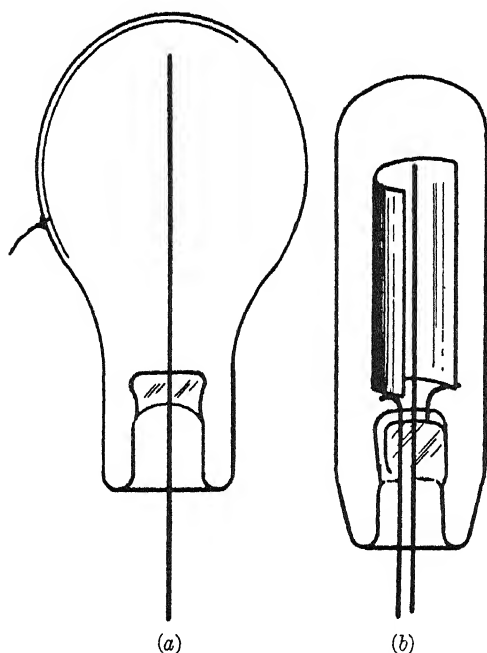


FIG. 44.—Typical photoelectric tubes. (a) Cathode deposited on bulb wall.
(b) Cathode deposited on metal plate.

which leaked off a charged metal surface were identical with cathode rays and thermionic electrons.

The modern photoelectric cell is not a metal plate in air but a two-electrode vacuum tube. One electrode, the light-sensitive cathode, is a deposit of a suitable material on the back wall of the bulb or else on a metal plate. The other electrode, the anode, is made of some convenient form and material, both of which are largely

dictated by the manufacturing process. Figure 44*a* and *b* illustrates these two types.

A complete study of the photoelectric effect includes a study of the number of electrons emitted and their initial velocities (as in the case of the thermionic effect) and the way in which these quantities are dependent upon the nature of the electrode surface, the frequency and the intensity of the incident light.

91. Relation between Current and Light Intensity.

The relation between photoelectric current and light intensity was investigated by a number of workers, including Lenard, Elster and Geitel, and Richtmyer, who showed that there was strict proportionality between the photoelectric current and light intensity. While many commercial tubes show slight deviations from linearity, this is believed to be due to some secondary effects. The primary photoelectric current itself is proportional to light intensity from the highest to the lowest intensities studied. While the intensity of the light controls the photoelectric current, *i.e.*, the number of electrons emitted, it has been shown that the initial velocities of the emitted electrons are entirely independent of the light intensity.

92. Spectral Sensitivity.

Early in the history of photoelectricity it was observed that the photoelectric response from any surface depended upon the portion of the spectrum used for illumination. In the case of the zinc studied by Hallwachs the ultraviolet was the most effective, while the red light did not cause the emission of any electrons. If a cathode is illuminated by equal amounts of light energy in different parts of the spectrum and the photoelectric currents measured, the results can be plotted as a curve, such as that shown in Fig. 45. This curve, showing the

relative photoelectric response to different wave lengths of light, is often called the *spectral-sensitivity curve*. The usual form of such a curve for most elements is a peak in the blue or ultraviolet end of the spectrum and a gradual falling off toward the red or long-wave end. The point where the curve cuts the axis at the red end of the spectrum is known as the long-wave limit. Any light of longer wave length than this will not cause the emission of any photoelectrons. The wave length of the long-wave limit, the position of the

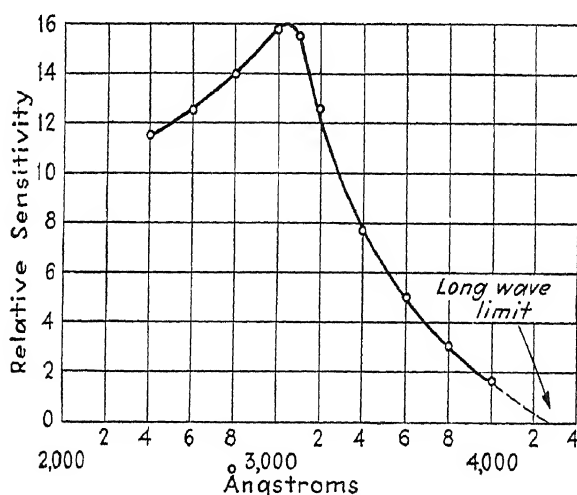


FIG. 45.—Spectral-sensitivity curve for sodium photoelectric surface in quartz bulb.

maximum in the short-wave end of the spectrum, and any other secondary maxima are definite characteristics of each photoelectric emitter. Practically all substances are photoelectrically active to some extent, but the effect is most marked for the metals. In the case of insulators the emission of a few electrons from the surface leaves them positively charged, and, since this charge cannot be neutralized by a flow of electrons from other parts of the circuit, as in the case of conductors, they remain charged and so prevent the emission of any

more electrons. The alkali metals show a greater response than any of the metals in the visible portion of the spectrum and hence have been used in practice to the greatest extent. It is very often stated that one metal is more photosensitive than another when the correct statement should be that it gives a greater response to the particular radiation used than the other. In making comparisons it must be remembered that the photoelectric response is a function of wave length.

The spectral-sensitivity curves for the alkali metals are particularly interesting, because they show a systematic shift in both the position of the maximum and that of the long-wave limit as we go down the series from lithium through sodium, potassium and rubidium to caesium. Thus lithium is said to be the least sensitive and caesium the most sensitive of this group. The real distinction is that most of the area under the curve lies in the ultraviolet for lithium and in the visible for caesium. Table XII gives the values of λ_0 , or the long-wave limit, for a number of the more common elements. From this table it can be seen that, with the exception of the alkali metals, most of the elements respond to ultraviolet light only. The sensitivity of the alkali metals extends farther into the visible end of the spectrum. Within these limits it is possible to choose emitters which are sensitive to any desired spectral region.

93. Quantum Theory of Photoelectric Emission.

Before discussing the relation between wave length and initial velocities, it is necessary to take up the theory of the photoelectric effect. There was no satisfactory theory to explain the observed facts of photoelectricity until after the development of the quantum theory of the nature of radiant energy. In 1905 Einstein proposed an explanation based on this theory, which was subsequently verified by Millikan. Conversely, the verifi-

cation of Einstein's theory also served as a very striking confirmation of the quantum theory.

According to the quantum theory, radiation consists of discrete units called "quanta." Each quantum has an amount of energy $h\nu$, where h is a universal constant and ν is the frequency of the radiation. Thus the energy of a quantum of light depends upon its frequency or wave length. It is greatest for blue and least for red radiation. Einstein assumed that each quantum of radiation absorbed by the photoelectric surface causes the emission of a single electron. He assumed, furthermore, that the electron acquires all of the energy of the light quantum which causes its emission. Its kinetic energy can then be expressed as

$$\frac{1}{2}mv^2 = h\nu \quad (89)$$

or, in terms of equivalent volts,

$$Ve = \frac{1}{2}mv^2 = h\nu, \quad (90)$$

where e is the charge of the electron and V is the voltage through which it would have to fall to acquire an amount of energy $\frac{1}{2}mv^2$. This equivalent voltage is also called the *stopping potential* because it represents the negative voltage which would have to be applied to the anode just to prevent the electron from reaching it. This represents the maximum possible energy which a photoelectron can have. In order to escape from the surface of the metal the photoelectron must do work against the same forces at the surface as in the case of thermionic emission. This work, as was shown in Chap. I, is ϕe . Accordingly, the escaping electron must lose this much energy in getting away from the surface. Thus it will finally escape with an amount of energy

$$Ve = h\nu - \phi e \quad (91)$$

The value of $h\nu$ which will just enable an electron to escape from the surface with zero velocity is $h\nu_0 = \phi e$ so that the equation becomes

$$Ve = h\nu - h\nu_0 \quad (92)$$

ν_0 is the frequency corresponding to the long-wave limit. No light of lower frequency (longer wave length) than this can possibly cause the emission of a photoelectron. $h\nu_0$ represents the minimum energy lost by an electron in escaping. If the electron escapes from deep down

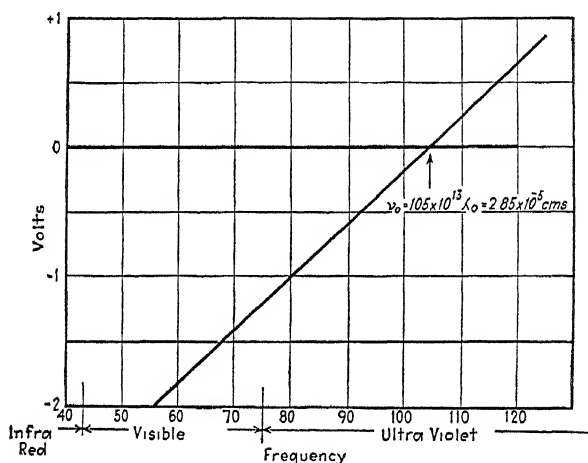


FIG. 46.—Relation between stopping potential and frequency of exciting light. (Millikan.)

under the surface of the metal, it may suffer a number of collisions on the way out and finally emerge with less energy than indicated by Eq. (92).

From this it can be seen that Ve is the maximum energy with which an electron escapes when its emission is caused by radiation of frequency ν . Einstein's equation then predicted that the maximum velocity (or stopping potential) of the escaping electrons must be a linear function of the frequency of the incident light. This was found to be the case in a classic experiment by Millikan. He illuminated alkali-metal surfaces with monochromatic light of various frequencies and measured

the corresponding values of the stopping potentials. A plot of the results is shown in Fig. 46. This shows that the stopping potential is proportional to frequency. The slope of the curve gives a value of $h = 6.56 \times 10^{-27}$, which is in excellent agreement with the value obtained by independent measurements. The intercept on the x axis gives the value of ν_0 . This can also be obtained (although less accurately) from the intercept of the spectral-sensitivity curve on the x axis.

The method of determining stopping potentials consists in applying a small negative voltage to the anode and increasing it until the current is reduced to zero. Inasmuch as this volt-ampere curve is asymptotic to the voltage axis, the exact value of the stopping potential determined depends upon the sensitivity of the measuring instrument used. This difficulty is partly overcome by plotting \sqrt{i} against V on the assumption that the lower part of the curve is a parabola. The stopping potential then is the intercept on the V axis. The assumption is not strictly true, but it does not introduce any large error.

This theory explains in a very satisfactory manner the relation between wave length and stopping potential and why the stopping potential is independent of light intensity. It does not, however, give any relation between the photoelectric current (number of electrons emitted) and the wave length.

If we substitute numerical values in the Einstein equation,

$$Ve = h\nu - \phi e$$

For the condition that an electron is just able to escape with zero velocity, *i.e.*, for $\nu =$ the frequency at the long-wave limit,

$$h\nu = \phi e$$

$$\phi = \frac{h\nu}{e} = \frac{12,336}{\lambda_0} \text{ volts} \quad (93)$$

where λ_0 is expressed in Ångström units.

From this relation, if the work function ϕ is known, the long-wave-length limit can be calculated and *vice versa*.

If we were to assume that one electron is emitted for each incident quantum, the relation between photoelectric current and wave length (for equal amounts of light energy at the various frequencies) would be as

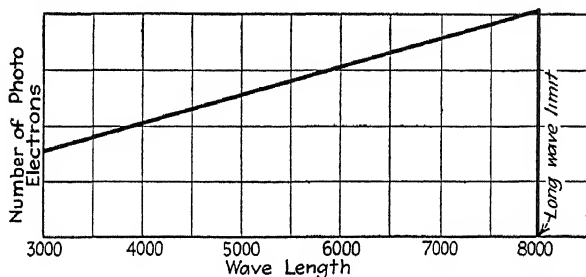


FIG. 47.—Relative number of photoelectrons emitted for equal amounts of energy in different parts of the spectrum. (Assuming 100 per cent efficiency.)

shown in Fig. 47. The photoelectric current would increase linearly with wave length because the number of quanta for a given amount of energy increases with increasing wave length (or decreasing frequency). This is because the energy of each quantum falls off with increasing wave length, according to the relation $W = h\nu$. At the long-wave limit the current would drop abruptly to 0. In practice we find that the relation is never of this form. On the contrary, the photoelectric current for equal amounts of energy falls off as we go from the shorter to the longer wave lengths and approaches zero asymptotically at the long-wave limit.

94. The Selective Effect.

A very interesting effect, called the *selective effect*, is characteristic of the alkali metals and some others.

These metals show a pronounced maximum in their spectral-sensitivity curve. If the curve is measured, using plane-polarized light instead of unresolved light, it is found that this selective effect is due to light polarized at right angles to the plane of incidence, while the curve taken with light polarized in the plane of incidence shows only a normal effect. This maximum is most pronounced for large angles of incidence in the neighbor-

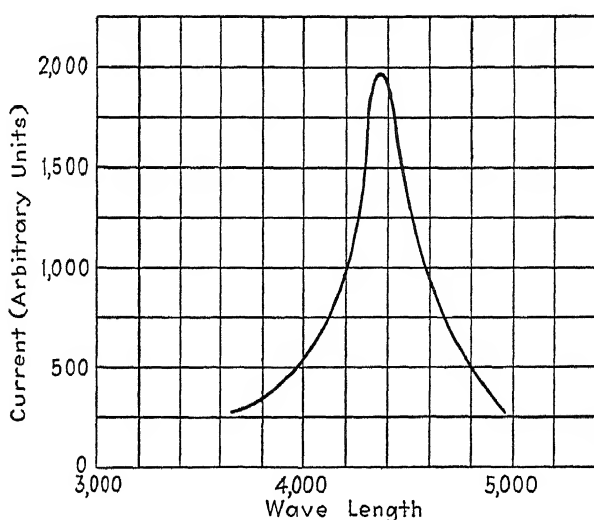


FIG. 48.—Spectral-sensitivity curve based on absorbed light energy, illustrating the selective effect. (*Fleischer and Dember, Z. tech. Phys.*, 7, 136, 1926.)

hood of 60 to 70 deg. The fact that light polarized at right angles to the plane of incidence is absorbed more than the component polarized in the plane of incidence is only sufficient to account for a ratio of photoelectric currents of 2 or 3, whereas at the selective peak the ratio may be as high as 20 or 30. The selective peak is shown in Fig. 48, where the relative photoelectric currents for equal amounts of *absorbed* light energy have been plotted as a function of wave length. These data are for unresolved light falling on a potassium surface.

95. Thin Films.

It has been stated that the shape of the spectral-sensitivity curve is characteristic for any metal. This statement is quite accurate for thick layers of pure metals, but the curve is greatly modified when the metal is studied in very thin layers, where the thickness of the layer is only a few atoms deep. This field was first investigated by H. E. Ives. If one of the alkali metals, for example sodium, is vaporized on to the surface of a polished platinum plate and the spectral-sensitivity curve is studied for various thicknesses of the sodium film, a series of curves will be obtained, such as shown

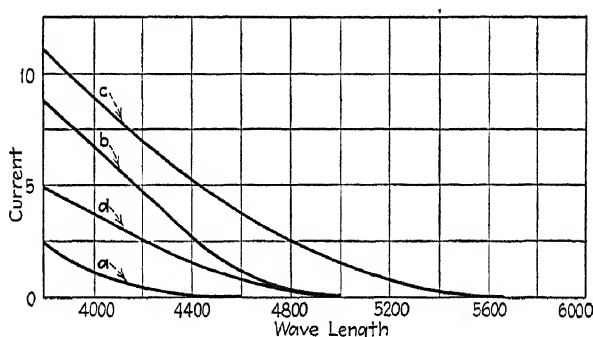


FIG. 49.—Spectral-sensitivity curves for sodium films of various thickness deposited on platinum; *a*, *b*, *c*, *d* in order of increasing thickness. (H. E. Ives, *Astrophys. J.*, **60**, 219, 1924.)

in Fig. 49. For films of the order of one atom thick the long-wave limit is relatively far in the red end of the spectrum, and, as the film grows thicker, it moves farther toward the blue. Similar behavior is shown qualitatively by other alkali and alkali-earth metals. The nature of the metal upon which the thin film is deposited influences the shape of the curve to some extent.

96. Oxides and Other Compounds.

Oxygen has a remarkable effect on the spectral sensitivity of the alkali metals. In the case of caesium,

which has been studied in greatest detail, a thin film of caesium upon a layer of oxides of caesium results in a spectral-sensitivity curve such as that shown in Fig. 50. This curve shows a new maximum at the edge of the infrared portion of the spectrum, and the long-wave limit has moved out to about 12000 Å. Compounds of caesium with other elements, particularly sulphur, have been found to have similar properties. The exact nature

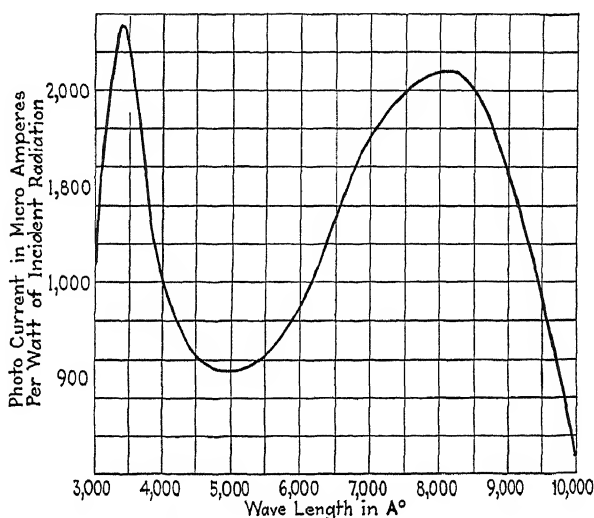


FIG. 50.—Spectral-sensitivity curve for caesium-oxygen-silver type of photoelectric tube.

of the oxides or other compounds which show this peculiar behavior is still a matter for conjecture. The preparation of such surfaces calls for a rather elaborate and at present empirical procedure.

Another compound of the alkali metals which affects the form of the spectral-sensitivity curve is the hydride. Like most of the other compounds it causes the long-wave limit to shift toward the red, although the shift is less pronounced than for oxygen. The hydride is easily formed by admitting a small amount of hydrogen into the cell and then passing a glow discharge between the

electrodes. The surface layers react with the activated hydrogen to form hydride. The excess of hydrogen is then pumped out. Potassium hydride has a characteristic iridescent purplish color which is easily recognized.

97. Red Sensitivity.

The shape of the wave-length-sensitivity curve has an important bearing on the practical application of photoelectric tubes. In any application it is desirable to obtain the maximum possible response from the photoelectric tube under the conditions of illumination. Accordingly, the photosensitive material used must be

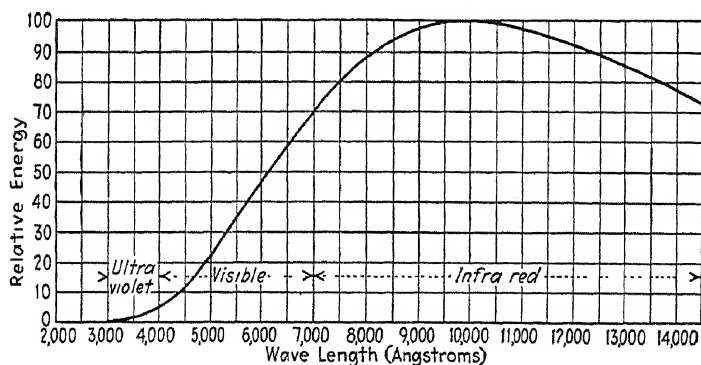


FIG. 51.—Spectral-energy distribution of radiation from an incandescent lamp operated at 2870°K.

one which responds to the kind of light used. For example, a zinc cathode would be quite useless with an incandescent-light source, as the zinc responds only to ultraviolet light. An incandescent-light source, such as a gas-filled tungsten lamp, radiates only about 8 per cent of its energy in the visible spectrum. The remainder is infrared. The distribution of the energy radiated is shown in Fig. 51. In order to get a large photoelectric current when the illumination is due to a light source of this kind, we require a cell which responds to infrared radiation. Such cells are not available, but at least we can approach this condition by using cells which have a

long-wave limit as far in the infrared as possible. The response of a photoelectric cell is obtained by multiplying the ordinates of the spectral-sensitivity curve by the corresponding ordinates of the energy-distribution curve of the source. If we consider two photoelectric tubes having spectral-sensitivity curves, such as those shown

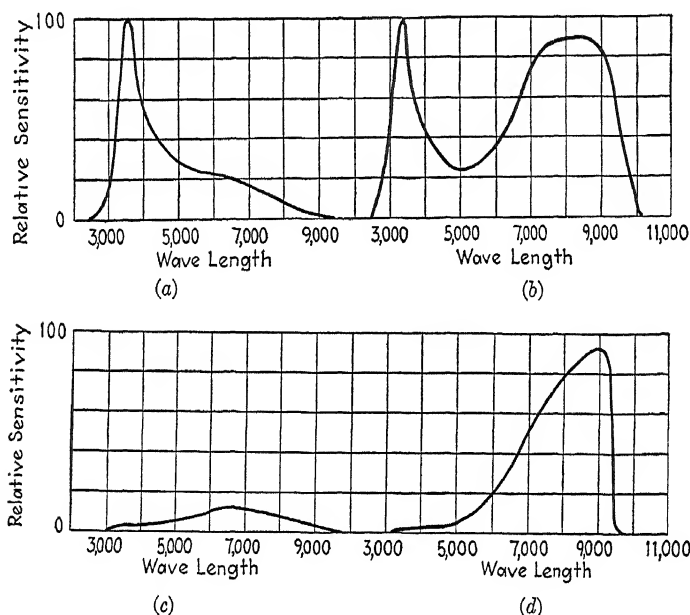


FIG. 52.—Response of different types of photoelectric tubes to a light source having the energy distribution shown in Fig. 51.

in Fig. 52*a* and *b*, respectively, illuminated by a light source having an energy distribution, such as that shown in Fig. 51, the responses of the two cells will be given by 52*c* and *d*. The area under *d*, *i.e.*, the total photoelectric current, is about six times that for *c*, because of the fact that the maximum photoelectric response lies in a region where the source radiates a large proportion of its energy. This explains the emphasis which is laid upon the production and utilization of “red-sensitive” tubes.

The common method of rating photoelectric tubes is in terms of microamperes per lumen. This method leads to some confusion unless the temperature of the

light source is specified as well. The reason for this is that the light source radiates much of its energy in the infrared to which the photoelectric tube is responsive to some extent. Another light source at a different temperature might radiate the same amount of visible light but a different amount of infrared, so that the photoelectric current would be different for the same number of lumens. Accordingly, it is quite important to specify the temperature of the source used. 2870°K. is the temperature most commonly used. It would really be more correct to filter out the infrared, but the current due to this radiation is used in practice, so this is not done.

98. Effect of Gases.

The presence of chemically active gases in photoelectric tubes is, of course, harmful owing to their reaction with the cathode surface. The sensitivity of cells, however, is greatly increased by the introduction of low pressures of inert gases. The volt-ampere characteristic of a photoelectric tube at constant illumination is exactly analogous to that for a hot cathode tube (such as Fig. 29, Chap. VIII) at constant filament temperature. The only difference is that saturation for photoelectric tubes usually takes place at relatively lower voltages, because the photoelectric currents are small so that space charge does not play such a large rôle. If a small pressure of gas is present and the voltage applied exceeds the ionizing voltage, ionization by collision takes place and the current is greatly increased. In practice, pressures up to 100 microns of the rare gases are used at anode voltages ranging from 90 to 180. Within approximately these limits the original photoelectric current from the cathode is increased from five- to tenfold. The ratio of the total current to the primary photoelectric current from the cathode is called the *gas amplification ratio*.

It is the ratio of the current at the normal operating voltage to the current at just below the ionizing voltage, both measurements being made at a relatively low light intensity. If the approximate limits of current or voltage mentioned above are exceeded, the discharge goes over to a glow discharge. This has all the characteristics described in Chap. IX and no longer responds to changes in light intensity. Argon and neon are the gases most

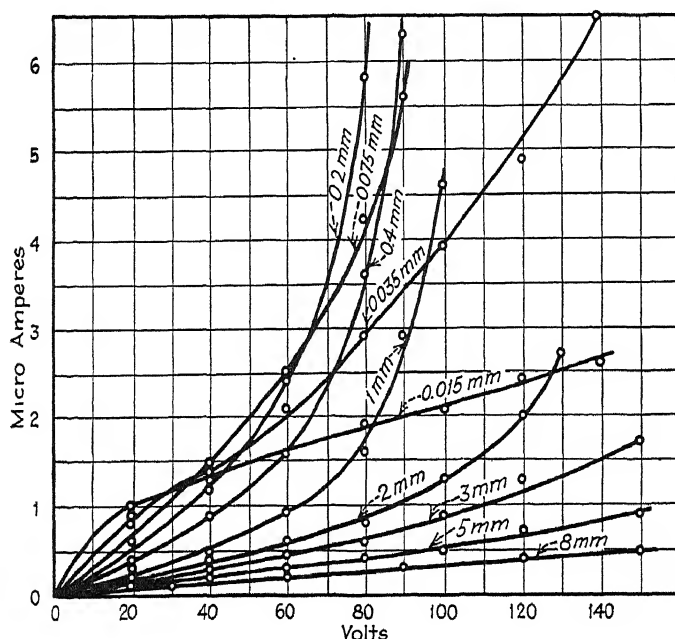


FIG. 53.—Phototube volt-ampere characteristics at various pressures of argon under constant illumination.

commonly used. Figure 53 shows the volt-ampere characteristics of a gas-filled cell at various pressures of argon. There is an optimum pressure at which the photoelectric response is a maximum. At lower pressures the probability of ionizing collisions is less, while at higher pressures the electrons lose energy by collisions before they acquire high enough velocities to ionize. The value of the optimum pressure depends upon the construction of the tube, and the value of the light inten-

sity and the applied voltage. Other considerations, such as tube noise and glow voltage, also enter into the choice of the proper pressure.

99. Time Lag.

Gas-filled photoelectric tubes differ from vacuum photoelectric tubes in another respect than their volt-ampere characteristic. This is their time lag. If a vacuum photoelectric tube is subjected to intermittent pulses of light, the response of the cell is independent of the frequency of these pulses. In gas-filled tubes, however, this is not the case, and, as the frequency of the

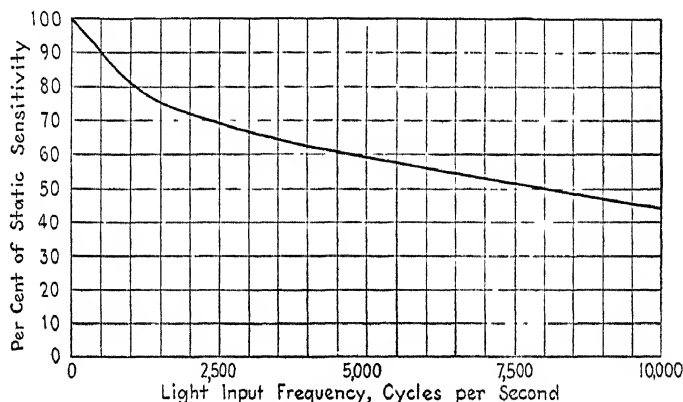


FIG. 54.—Effect of sinusoidal variation of light flux on sensitivity of gas-filled phototube.

pulses is increased, the response of the cells falls off. This effect is shown in Fig. 54. It is due to a time lag in the photoelectric response, *i.e.*, the variation in photoelectric current does not accurately reproduce the variation in light intensity.

100. Effect of Temperature.

The photoelectric effect within wide limits is independent of temperature. For a long time it was thought to be entirely independent of temperature, but later experiments have shown a decrease in photosensitivity

at liquid-air temperatures for the alkali metals, and a rather abrupt rise at about $600^{\circ}\text{C}.$ for platinum. There are *apparent* changes in photosensitivity with temperature which are produced by the formation or destruction of surface films of gas or by other surface changes.

Measurements of photoelectric currents at high temperatures are somewhat complicated for photoelectric cathodes, such as caesium oxide, by the fact that these materials are good thermionic emitters, and, since their surfaces are large, the thermionic currents may become appreciable. For example, the constants A and b_0 for a caesium oxide type of photoelectric tube are $A = 10^{-3}$ and $b_0 = 8300$. A common type of tube has a cathode area of 110 sq. cm. Accordingly, at $50^{\circ}\text{C}.$, the thermionic emission from this surface would be 10^{-9} amp. Thus, even with the cell in the dark, there would be a current flowing. At low light intensities this thermionic current might be quite large compared with the photoelectric current.

101. Dark Currents.

The early literature of photoelectricity contains many references to *dark currents*. These currents were observed to flow even when the cell was not illuminated, hence their name. They actually have no connection with the photoelectric effect but are merely leakage currents. With improved knowledge of methods of insulating, these currents no longer cause trouble. Dark currents of the thermionic type mentioned above were not experienced with the earlier relatively insensitive cells.

102. Fatigue.

Another term used in the earlier literature is *fatigue*, which was used to describe a gradual decrease in photoelectric current during the period of illumination. To some extent this has disappeared with improved methods

of exhaust, but certain cells, particularly those containing gas, show changes in sensitivity when illuminated. These changes are sometimes decreases and sometimes increases, depending upon the type of cell and its history. No satisfactory explanation of this effect has been found.

103. Efficiency of Photoelectric Emission.

The actual efficiency of photoelectric emission in terms of electrons per quanta is surprisingly low. If we refer

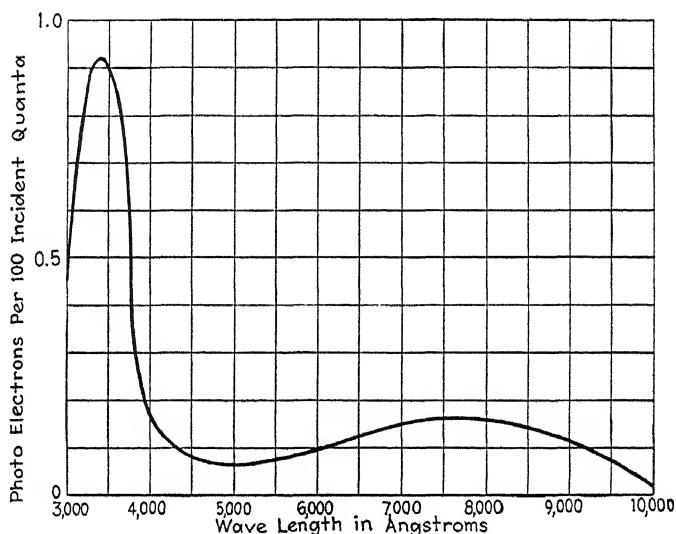


FIG. 55.—Efficiency of photoelectric emission at various wave lengths.

to Fig. 50 and replot these data in terms of number of electrons per hundred quanta (rather than current) as ordinates, as shown in Fig. 55, we shall find that the maximum value comes at practically the same wave length as before and corresponds to a value of about one electron for each 100 incident quanta. In terms of absorbed rather than incident light the value is somewhat higher.

104. Comparison with the Human Eye.

A comparison between the photoelectric cell and the human eye as detectors of radiation is interesting.

The visual threshold, *i.e.*, the smallest amount of light which can be detected by the unaided eye, is the light received from a sixth-magnitude star or 9.6×10^{-13} lumen (assuming the diameter of the pupil to be 6 mm.). A highly sensitive photoelectric tube has a sensitivity of about 600 microamp. per lumen and would give a current of 5.8×10^{-16} amp. for this much light. It is possible to measure currents much smaller than this. Accordingly, a photoelectric cell with a good amplifier is a more sensitive detector of visible radiation than the eye. When the two are compared for the same low *intensity* rather than the same total flux, the comparison is more favorable for the photoelectric cell, as its light-collecting area is much greater than that of the pupil of the human eye.

105. The Use of Filters.

Filters are very often used in making photoelectric-cell measurements to limit the response to some one portion of the spectrum. For instance, if photoelectric-cell measurements are to be made of the variation in transmission with concentration of a solution which absorbs red and transmits blue light, a red filter is used so that the cell receives only that component of the light which changes. The blue, which is not much affected by concentration, would serve only to increase the total photoelectric current and to decrease the percentage variation. A general rule is to use a filter of the color which is most strongly absorbed by the material under investigation.

106. Various Types of Construction.

Since only a fraction of the incident light is absorbed at the photoelectric surface, attempts have been made to increase the yield by designing tubes so that the light will undergo a number of reflections, thus obtaining a photoelectric effect from the light which would otherwise be

reflected at the first surface. One such construction is shown in Fig. 56, where the cathode was made V shaped. Another is the common spherically shaped bulb where the light must make several reflections before escaping from the window, provided that it originally enters the tube a little off center.

Photoelectric tubes are made in various sizes. The only advantage of large tubes is that they have a larger light-collecting surface. The response of a photoelectric surface to a light depends upon the total flux or total amount of light falling upon the surface and not on its intensity. The response from a given quantity of

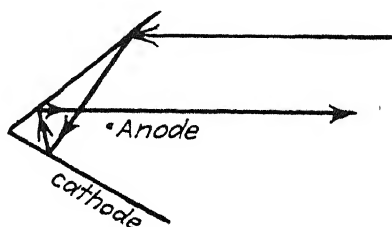


FIG. 56.—V-shaped cathode designed to give multiple reflections.

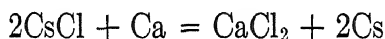
light is the same regardless of whether it is concentrated on a small spot or spread out over a large area. For this reason there is no advantage to be gained by using a larger tube than is necessary to intercept all the available light. In many cases it is convenient to collect the light by means of large lenses or mirrors and concentrate it on a small tube instead of using a tube with a very large light-collecting area.

For many purposes where it is desired to make measurements of ultraviolet radiation, photoelectric tubes are made in quartz bulbs instead of glass, as the latter, of course, do not transmit ultraviolet.

The life of photoelectric tubes is practically indefinitely long, as nothing is used up in the course of their operation.

107. Manufacturing Technique.

A very interesting feature of the manufacture of photoelectric tubes is the method used for introducing the alkali metal into the bulb. The earliest method is to place a piece of the metal in the end of a tube which is then heated by a Bunsen flame and distilled into the photoelectric cell, leaving most of the impurities behind. The distillation tube is then sealed off at the constriction. Where a higher degree of purity is required, the metal may be distilled through a series of bulbs. Another method involves the actual preparation of the metal *in vacuo*. A salt of the alkali metal, such as caesium chloride, is mixed with a reducing agent, such as calcium, and placed in the distillation tube. When this is heated by a Bunsen flame, reduction takes place according to the formula



The caesium can then be distilled out into the bulb as before. A modification of this procedure is to press the alkali-metal salt and the reducing agent into a pellet, which is placed in a nickel (or other metal) capsule inside of the bulb. When this is heated by high-frequency induction, the reaction takes place and the alkali metal distills out into the bulb. In the case of caesium the reagents used at present are caesium dichromate and silicon.

A third method involves a decomposition reaction. A compound, such as the nitride of the element, is painted upon a convenient electrode. When this is heated, it decomposes and the nitrogen is pumped out while the alkali metal remains.

Another method consists in electrolyzing the alkali metal through the bulb wall. The end of the bulb is

immersed in a bath of a molten alkali-metal salt, such as sodium nitrate, which melts at 312°C. An electrode placed in the bath is connected to the positive side of a direct-current source of potential of 100 or 200 volts. A filament inside of the bulb is operated at a high enough temperature to yield an electron current of a few milliamperes. This filament is connected to the negative side of the line. Under the influence of the field, positive sodium ions diffuse through the bulb walls to the inner surface where they pick up electrons from the hot cathode and become neutral sodium atoms. This process is really just the replacement of sodium atoms in the glass by atoms from the bath. A practically unlimited supply of pure sodium can be introduced in this manner without damage to the glass. Other alkali metals cannot be introduced through an ordinary soda-lime glass bulb without producing strains which crack and disintegrate the glass, because the other alkali-metal atoms are larger in diameter than sodium. They can, however, be passed through bulbs of special composition, but these glasses are difficult to work and have many undesirable characteristics. Since electrolysis through the bulb wall follows Faraday's laws, it permits exact control of the amount of alkali metal.

Another method which is used in experimental work but not in factory production also permits of control of the amount of metal introduced. The alkali metal is placed in a small bulb connected by a capillary with the photoelectric cell. If the bulb and capillary are maintained at a known temperature, the rate at which the alkali-metal vapor diffuses through the capillary may be calculated from Knudsen's formula

$$Q = \frac{(P_2 - P_1)D^3}{2.394L\sqrt{\rho_1}} \quad (94)$$

where $P_2 - P_1$ = difference in pressure

L = length of capillary

D = diameter of capillary

ρ_1 = density of gas at pressure of 1 barye
and temperature of the tube.

TABLE XII.—PHOTOELECTRIC LONG-WAVE LIMIT FOR VARIOUS
ELEMENTS

Element	λ_0 , Ångströms
Platinum	2570
Nickel	3050
Tungsten	2300
Cadmium	3140
Lithium	5200
Sodium	5830
Potassium	7000
Rubidium	>10000*
Caesium	>10000*

* Thin films.

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CHAPTER XII

PHOTOCONDUCTIVITY

108. Selenium and Selenium Cells.

Another electronic phenomenon which is intimately related to the photoelectric effect discussed in the previous chapter is that of photoconductivity. This is sometimes called the *internal photoelectric effect*. Many substances show an increase in conductivity upon exposure to light. This is the result of the liberation of electrons within the conductor by light. In the case of photoconductivity, however, these electrons do not escape from the surface of the conductor but stay within the metallic circuit. A great many compounds and a few elements show this effect. It is most striking in selenium and was first discovered in this element. Selenium exists in several allotropic forms. One of these is a black vitreous non-conductor. On heating above 180°C. this slowly changes over to a gray crystalline form which is the light-sensitive modification. The discovery of its light-sensitive properties was made by Willoughby Smith in 1873. He used sticks of the gray form as resistances in some transatlantic-cable work and was troubled by their variability until he found that it was due to the effect of light upon them.

A description of typical cells and their behavior had best precede the theory of the effect. Since selenium has a very high resistance, a number of forms of cell have been made in order to give higher conductivities than can be obtained by sticks or rods of the metal. The aim is to obtain the maximum possible illuminated

area with the lowest possible resistance. One of the earliest forms, which is shown in Fig. 57*a*, consists of a pair of wires closely spaced and wound around an insulator. Selenium is heated and smeared over the surface which thus consists essentially of a long, narrow, thin strip of selenium bridging the gap between the two wires which act as terminals. A similar result is achieved in a slightly different manner, as shown in Fig. 57*b*. A piece of glass is gold plated and the gold is scratched in a zigzag line, thus forming two electrodes with a very long and narrow surface of separation. A thin layer of

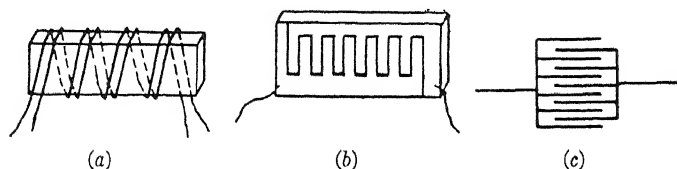


FIG. 57.—Three types of selenium cell construction.

selenium is then formed on the plate, bridging this gap. In a third form, shown in Fig. 57*c*, the two plates are made in a form very similar to the two sets of plates of an air condenser. The space between the plates is filled with selenium. In every case the cell must undergo an annealing process in order to convert the selenium to the light-sensitive form. Its properties will depend upon the method of preparation and deposition of the selenium and on the way in which the annealing is carried out, as well as on the construction of the cell. The cells are usually protected from the atmosphere by enclosing them in an evacuated glass bulb, or coating them with a transparent lacquer.

109. Relation between Current and Light Intensity.

When a source of e.m.f. is connected across the terminals of a selenium cell, a current flows. When the cell is in the dark, this is called the *dark current*. If the cell

is illuminated, the current increases. It does not, however, increase in direct proportion to the illumination but in accordance with the law

$$i = kI^{1/2} \quad (95)$$

where i is the increase in current, due to the illumination I , over the dark current. Typical values of current at different light intensities for two different voltages are given in Table XIII. The same results are shown graph-

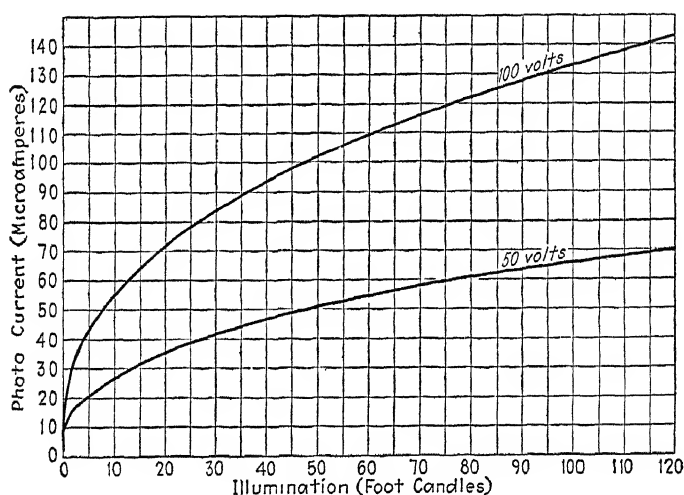


Fig. 58.—Illumination current characteristic of selenium cell.

ically in Fig. 58. From these data it can be seen that the change in photoelectric current for a given change in light intensity is much greater at low intensities than at high intensities.

Because of the fact that the photoelectric current in selenium is not directly proportional to the intensity of the illumination but to its square root, the area illuminated in selenium cells becomes important. A given light will produce different results, depending upon the area upon which it falls. In the case of photoemissive cells this is not so, as the response depends upon the quantity of light only. The effect is also complicated by the fact that a change in conductivity is produced between the

electrodes even though the light falls upon a region outside of the interelectrode space.

110. Time Lag.

A very noticeable feature of the photoelectric response of selenium is its time lag. If the illumination is changed suddenly, the current does not change to the new value instantaneously but lags behind the illumination by an appreciable time. This effect is shown in Fig. 59, where

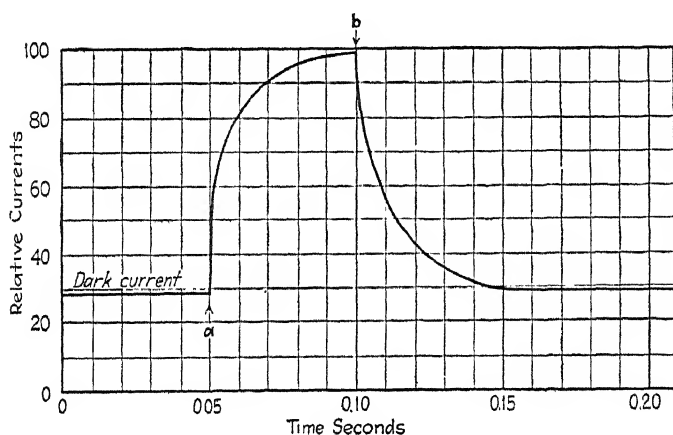


FIG. 59.—Time lag in a selenium cell.

the ordinates represent current and the abscissae time. At point *a* the cell is suddenly exposed to strong light. The photoelectric current does not reach its final value until several minutes have elapsed, although it attains 95 per cent of its final value in 0.03 sec. Similarly, at *b*, where the light is turned off, the current does not fall to the dark value at once but requires several minutes to reach its final value. The amount of this time lag depends upon the type of cell as well as its history, *i.e.*, the conditions of operation just before the change in light. All selenium cells show this effect, although not all to the same extent. The photoelectric effect in selenium is greatly increased at low temperatures.

111. Spectral Sensitivity.

Selenium has a peak in its spectral-sensitivity curve in the red at about 7000 Å., as is shown in Fig. 60. The exact shape of the curve depends upon the manufactur-

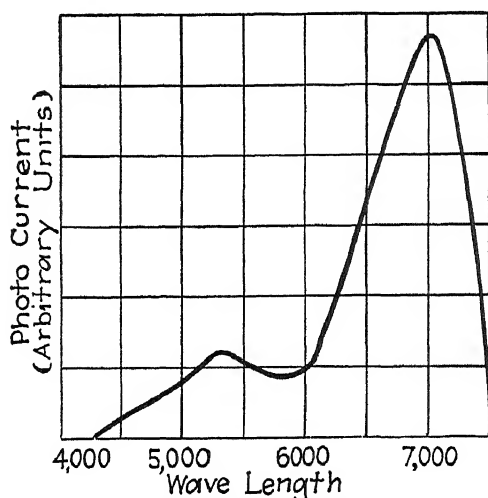


FIG. 60.—Spectral sensitivity of selenium cell. (Nicholson.)

ing process, temperature and time of annealing, purity of the selenium, etc.

112. Cuprous Oxide.

After selenium, the most light-sensitive substance known is probably cuprous oxide (Cu_2O). Crystals of this substance can be prepared by oxidizing metallic copper at about 1000°C. in air and then removing the scale of cupric oxide (black oxide) by dissolving in aqua regia or by chipping it off. The red translucent crystals of the cuprous oxide, when clamped between metal electrodes or provided with sputtered or evaporated electrodes, show photoelectric effects in many ways similar to selenium. Cuprous oxide is one of the few compounds which show a large photoelectric effect when prepared in the laboratory. A large number of heavy

metal sulphides listed in Table XIV are photoelectrically active. These are usually classed as semiconductors and have indices of refraction greater than 2. It is only the natural minerals, however, which are photosensitive. The synthetic material is not.

113. Molybdenite.

One of the most active of these heavy metal sulphides is molybdenite. The activity is not uniform throughout the material but occurs in certain highly localized spots.

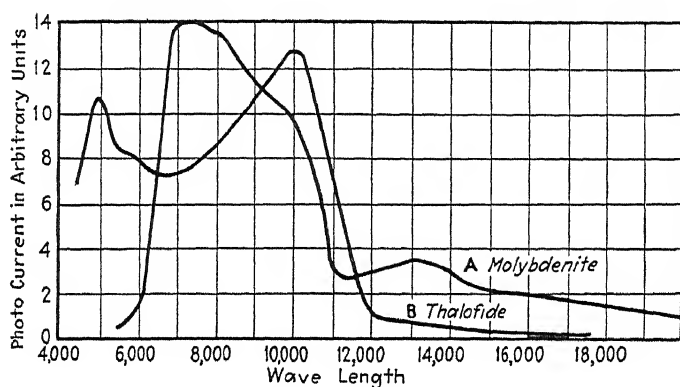


FIG. 61.—Spectral sensitivity of molybdenite and thalofide.

These spots are extremely small in area. The spectral sensitivity for molybdenite is shown in Fig. 61A. In addition to its change in conductivity on exposure to light, molybdenite actually generates a small e.m.f. so that a current may be obtained from an illuminated crystal without any externally applied voltage. The other compounds listed in Table XIV all show much smaller effects. Almost all of them show large fatigue effects, *i.e.*, the photoelectric effect decreases with time on exposure to light.

114. Thallium Oxysulphide.

Thallium oxysulphide (thalofide), a synthetic compound, is also photosensitive, particularly in the infrared.

Its spectral-sensitivity curve, shown in Fig. 61*B*, has a peak in the infrared at about 10000 Å. It shows large fatigue effects and the photoelectric current under any one condition of operation is greatly influenced by the operating conditions immediately preceding.

The only one of these photoconductors which has been commercially applied with any great degree of success is the selenium cell. The advantage which it possesses over the photoemissive type of cell is that its currents are relatively large, so that it is often possible to operate relays or other devices without amplification. Its disadvantages are its dark current, lack of proportionality in response to illumination, its large temperature coefficient and its time lag.

115. Theory of Photoconductivity.

On first sight the phenomena in photoconductors appear to be very complex, and for a long time there was no satisfactory theory to account for them. Gudden and Pohl, however, have shown that in insulating crystals, such as diamond, zincblende, cinnabar, and stibnite, there is a fundamental effect of a very simple nature. In most cases this is obscured by several much larger secondary effects. In order to observe the fundamental effect, it is necessary to use very low light intensities and very short periods of illumination and to make the observations on single crystals. Under these conditions it is found that the photoelectric current is directly proportional to the illumination and follows the illumination without any time lag. Furthermore, measurements show that one electron is liberated for each light quantum absorbed; *i.e.*, if the number of electrons emitted for a unit amount of absorbed energy is plotted as ordinates against wave length as abscissae, the curve of Fig. 62*A* is obtained. This is similar to the theoretical curve of Fig. 47, Chap. XI. When the electron yield is

referred to the incident energy rather than the absorbed energy, the curve takes the form of Fig. 62*B*. The effect of the light appears to be to form pairs of charges in the crystal, one pair of charges being formed for each quantum absorbed. The negative charges move freely through the crystal and constitute the true primary photoelectric current. The positive charges are left behind and produce space-charge effects quite analogous to those observed in vacuum tubes. If the light intensity used is low and the period of illumination is short,

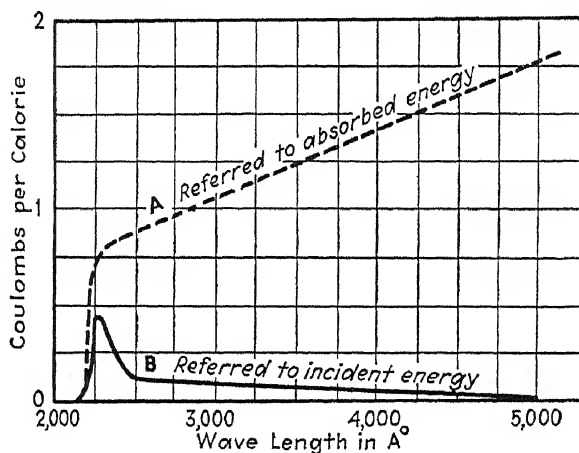


FIG. 62.—Spectral sensitivity of diamond. (Gudden and Pohl.)

the effect of this space charge is negligible. With high intensities and longer periods of illumination its effect becomes more pronounced. This positive space charge can be removed by illuminating the crystal with red light. This restores it to its original condition and on repeating the illumination reproducible results can be obtained.

The relation between voltage and current is shown in Fig. 63. The current increases with voltage and eventually reaches a saturation value. The saturation voltage does not depend upon the wave length or the intensity of the light. The more perfect the crystal is, however, the more pronounced is saturation. It appears

as if imperfections and cracks in the crystal impede the motion of electrons through it, particularly at low field strengths.

The effect of temperature on the primary current at first appears complex, but when certain effects are taken into consideration it is found that the primary current is independent of temperature as far down as -250°C . This is not necessarily true of the secondary currents.

Some crystals, such as rock salt and other alkali halides, do not show any photoelectric effect in their original condition. When they are exposed to x-rays,

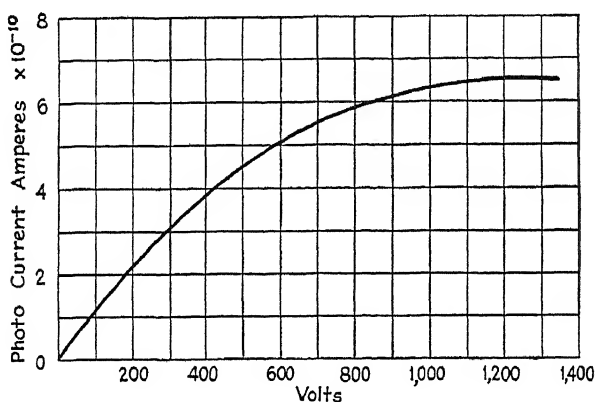


FIG. 63.—Volt-ampere characteristic for a zincblende crystal. (*F. Nix, Rev. Mod. Phys.*, 4, 726, 1932.)

or to ultraviolet radiation, a coloring of the crystal takes place and they show photoconductivity. The same coloring and photoconductivity can be produced by impregnating the crystal with alkali vapor by heating it in a closed vessel containing the vapor of the alkali metal. The spectral sensitivity of these colored crystals coincides with their optical and absorption curves.

For long periods of illumination and high light intensities the primary photoelectric currents no longer obey the simple laws. Under these conditions the primary currents give rise to much larger secondary currents. It is these secondary currents which are ordinarily

TABLE XIII.—PHOTOELECTRIC CURRENT AT VARIOUS VALUES OF ILLUMINATION FOR A SELENIUM CELL

Illumination, foot-candles	Milliamperes at	
	100 volts	50 volts
110	138	69
90	128	64
70	116	58
50	103	51.5
30	85	42.5
20	73	36.5
10	56	28
5	43	21.5
2.5	35	17.5

TABLE XIV.—MINERALS EXHIBITING PHOTOCONDUCTIVITY

Formula	Substance	Magnitude of effect
Ag_3AsS_3	Proustite	Great
Ag_9AsS_6	Pearceite	Medium
AgI	Iodyrite	Medium
Ag_2O	Silver oxide	Medium
Ag_2S	Acanthite	Great
Ag_2S	Argentite	Great
AgSbS_2	Miargyrite	Medium
Ag_3SbS_3	Pyargyrite	Medium
Ag_5SbS_4	Stephanite	Medium
Ag_9SbS_6 ..	Polybasite	Medium
Bi_2S_3	Bismuthinite	Very great
Cu_2O	Cuprite	Medium
$(\text{Cu}_2\text{Pb})_3\text{Sb}_2\text{S}_6$	Bournonite	Great
MoS_2	Molybdenite	Medium
PbS	Galena	Medium
$\text{Pb}_2\text{Sb}_2\text{S}_5$	Jamesonite	Medium
$\text{Pb}_3\text{Sb}_2\text{S}_6$	Boulangerite	Great
Sb_2S_3	Stibnite	Small
Se	Selenium	Medium

observed in semiconductors and which mask the underlying primary currents. There is no satisfactory explanation for them. The most important characteristics of the secondary currents are that they do not show a saturation in current with increasing voltage. Furthermore, the spectral sensitivity is to some extent dependent upon the voltage.

An interesting feature of the spectral sensitivity of photoconducting crystals is that it is not (as might be expected) a maximum for the absorption band, but the maximum actually occurs at the short-wave edge of the absorption band. The spectral-sensitivity curve usually shows a maximum with a steep slope on the short-wave side and a gradual slope on the long-wave side.

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CHAPTER XIII

THE PHOTOVOLTAIC EFFECT

116. Cuprous Oxide Cells.

A type of photoelectric effect which is found in many substances of the rectifier type has recently assumed commercial importance. This effect is sometimes called the *photovoltaic effect*, although different writers have different designations for it. Some commercial types of cells using this effect have been called photonic cells. It is very readily observed in cuprous oxide. For this

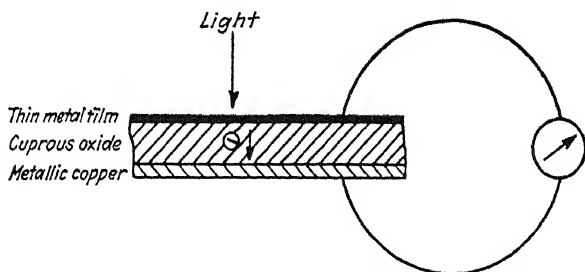


FIG. 64.—Current flow in cuprous oxide type of photo cell.

purpose the cuprous oxide must be formed on a copper surface. A cuprous oxide rectifier unit is ideal. The metallic copper serves as one electrode and contact can be made with the other by either sputtering or evaporating a thin film of metal on the surface, or by pressing a grid of wire mesh against the surface. If the oxide surface is illuminated, a current will flow in the external circuit from the cuprous oxide to the copper. This means that, within the material, electrons are passing from the cuprous oxide to the copper. This is just the reverse of the direction of electron flow when the cuprous oxide and

copper combination is used as a rectifier. The circuit and the direction of current flow are shown in Fig. 64. If the resistance of the external circuit is low, the response of such a photoelectric cell will be very nearly proportional to the illumination. Under these conditions the photoelectric currents expressed in amperes per lumen are of the same order of magnitude as for photoemissive cells. One commercial type gives a current of about 60 micro-amp. per lumen.

117. The Sperrschicht.

This type of photoelectric effect is explained on the basis of a "blocking layer" at the interface between the cuprous oxide and the copper. In the German literature this is referred to as a *Sperrschicht*. This layer is extremely thin. Various investigators have estimated its thickness to be 3×10^{-6} to 3×10^{-8} cm. (approximately 1 to 100 atomic diameters) and its capacity 25,000 cm. per square centimeter. When such a cuprous oxide and copper combination is used as a rectifier, the electrons pass from the copper to the oxide readily but are unable to pass in the opposite direction. When used as a photoelectric cell, the electrons which are liberated by light in the cuprous oxide readily pass across the blocking layer. The result is an e.m.f. tending to return the electrons. They can return to the cuprous oxide either by going back across the blocking layer or by returning through the external circuit. The current in the external circuit, therefore, will depend upon the relative resistance of the two paths. The resistance of the cell is made up of several parts: the resistance of the external circuit, the resistance of the blocking layer and the resistance of the cuprous oxide itself. Because of the last it is to be expected that the properties of the cell will depend in part on the thickness of the oxide layer. The resistance of the cuprous oxide which is

effective is the resistance in the direction parallel to the surface, as may be seen from a consideration of the electron paths of Fig. 65.

The thickness of the layer also influences the properties of the cell in another way. The electrons which succeed

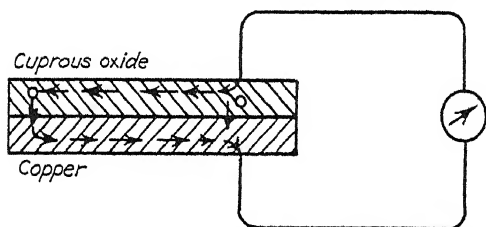


FIG. 65.—Electron paths in cuprous oxide photo cells.

in crossing the boundary between the oxide and the copper are those which are liberated near the boundary. Consequently, the effective portion of the light is that

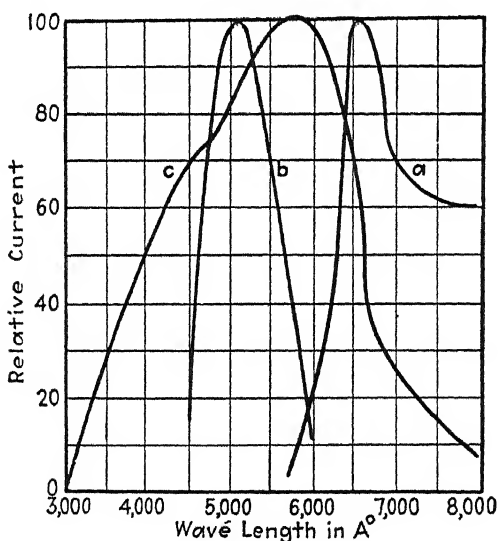


FIG. 66.—Spectral sensitivity of various types of photovoltaic cells. *a.* Cuprous oxide, back effect. *b.* Cuprous oxide, front effect. *c.* Selenium on iron.

which has already passed through a considerable thickness of oxide. Cuprous oxide is transparent to red and absorbs the short-wave end of the spectrum. Thus the light which penetrates to the region of the blocking film

is red light and accordingly the cells are relatively red sensitive. The spectral-sensitivity curve for such a cell is shown in Fig. 66a. The spectral sensitivity will depend upon the thickness of the cuprous oxide layer, and the cell will be more red sensitive the thicker the layer.

118. Front-effect Cell.

If the sputtered or evaporated terminal is applied upon a surface which has been specially prepared, a different effect is observed. The current in the external circuit is now in the reverse direction, *i.e.*, electrons go from the cuprous oxide to the sputtered terminal within the cell. This type of cell is called a *front-effect cell* to distinguish it from the previous type, which is called a *back-effect cell*. The front effect, since it is due to the light first absorbed, shows a relatively high blue sensitivity as compared with the back effect. Figure 66b shows a front-effect spectral-sensitivity curve. The back effect also exists in such a cell but the front effect predominates. The proper procedure for making a front-effect cell has not been disclosed in the literature. The effect from a well-made front-effect cell is usually larger than that from a back-effect cell.

119. Other Photovoltaic Cells.

Qualitatively the same type of effect is shown by a thin film of selenium on iron with a suitable sputtered or evaporated surface to serve as one terminal. The spectral sensitivity of a selenium-on-iron type of cell is shown in Fig. 66c.

There are also electrolytic types of photovoltaic cells. A discussion of these, however, is outside the scope of this book.

The e.m.f. generated by photovoltaic cells is of the order of a few millivolts. Accordingly their field of

usefulness is limited to illumination intense enough to yield photoelectric currents which can operate control devices or indicating instruments without amplification.

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APPENDIX A

RICHARDSON'S EQUATION

According to the kinetic theory of gases, the relation between the number of molecules per unit volume at any two points, in thermal equilibrium, and the work required to bring a molecule from one point to the other is

$$n = n_1 e^{-\phi/kT} \quad (96)$$

where n and n_1 = concentrations of molecules at the two points

ϕ = the work required to bring a molecule from one point to the other

k = the Boltzmann constant

T = absolute temperature.

Let us assume a hot filament in an evacuated space with walls at the same temperature as the filament. The filament will emit electrons until the number which return to it are just equal to the number leaving it. We may consider these electrons as atoms of a perfect gas. When equilibrium conditions have been reached, there will be n_1 electrons per unit volume in the interior of the filament and n electrons in a unit volume of the space outside of the filament, the relation between n and n_1 being given by Eq. (96). The work done in transferring an electron from within the filament to the space outside is ϕ , already defined as the work function.

According to kinetic theory, the number of electrons which strike a unit area of the filament surface per second is related to the total number present in a unit volume

of the space outside of the filament according to the equation

$$N = n\sqrt{\frac{kT}{2\pi m}} \quad (97)$$

where N = number of electrons striking the unit area per second

n = number of electrons per unit volume in the space outside of the filament

m = mass of electron.

Under equilibrium conditions, the number of electrons which return to the filament must be just equal to the number emitted per unit area of surface.

Accordingly, the number of electrons emitted

$$N = n_1 \epsilon^{-\phi/kT} \sqrt{\frac{kT}{2\pi m}} \quad (98)$$

The electron current $I = Ne = n_1 e \sqrt{k/2\pi m} T^{1/2} \epsilon^{-\phi/kT}$

If n_1 and ϕ are assumed to be independent of T , this may be written

$$I = a T^{1/2} \epsilon^{-b/T}$$

Reference

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APPENDIX B

THE SCHOTTKY EQUATION

The work which an electron must do against image forces to escape from the surface of a metal in the absence of any accelerating field is

$$e\phi = \int_0^{\infty} F(x)dx \quad (99)$$

If an accelerating field E is applied, it will exert a force Ee upon the electron. This force is opposed to the image forces. At some distance x_0 from the cathode, the two forces must be equal. Any electron with sufficient energy (high enough initial velocity) to reach this critical plane will be able to escape, for, once it reaches this plane, it will be assisted by the external field.

If we assume that the image force follows the inverse-square law

$$F(x) = \frac{e^2}{4x^2} \quad (100)$$

and for $x = x_0$

$$F(x) = \frac{e^2}{4x_0^2} = Ee$$

and

$$x_0 = \frac{1}{2}\sqrt{\frac{e}{E}} \quad (101)$$

The assumption of the inverse-square law is justified for most practical cases. For example, a potential of 100 volts applied between a filament 1×10^{-3} cm. in diameter and a concentric cylindrical anode 1 cm. in diameter will give a field strength at the surface of the filament

of 3×10^4 volts per centimeter. Under these conditions, x_0 would be approximately 10^{-6} cm., or about 100 atom diameters. At this distance it is quite safe to assume the inverse-square law.

Let ϕ' be the effective work function, *i.e.*, the work function in the presence of an accelerating field. Then the work an electron must do to escape from a metal in the presence of an accelerating field is

$$\begin{aligned}
 e\phi' &= \int_0^{x_0} [F(x) - eE] dx & (102) \\
 &= \int_0^\infty F(x) dx - \int_{x_0}^\infty F(x) dx - \int_0^{x_0} E dx \\
 &= \phi e - \int_{x_0}^\infty \frac{e^2}{4x^2} dx - \int_0^{x_0} E dx \\
 &= \phi e - \frac{e^2}{2} \sqrt{\frac{E}{e}} - \frac{Ee}{2} \sqrt{\frac{e}{E}} \quad [\text{substituting Eq. (101)}]
 \end{aligned}$$

Therefore

$$\phi' = \phi - (Ee)^{1/2} \quad (103)$$

If we put this value of the work function in the emission equation

$$I_0 = AT^2 \epsilon^{-\phi_0/T}$$

where I_0 represents the emission for zero field, it takes the form

$$\begin{aligned}
 I &= AT^2 \epsilon^{-\frac{e}{kT}[\phi - (Ee)^{1/2}]} \\
 &= AT^2 \epsilon^{-e\phi/kT} \epsilon^{e(Ee)^{1/2}/T} \\
 &= I_0 \epsilon^{\frac{4.389}{T} E^{1/2}} & (104)
 \end{aligned}$$

where E is in volts per centimeter. Thus the effect of the accelerating field is to increase the emission by the factor $\epsilon^{\frac{4.389}{T} E^{1/2}}$. This factor is ordinarily not taken into account in making calculations of thermionic emission.

The significance of the Schottky theory lies in its usefulness in obtaining information about the nature of

the fields close to surfaces. Experiment has shown that the Schottky equation is valid for high field strengths, but for low fields the current falls much more rapidly than is predicted by the theory. This is true particularly in the case of surfaces such as caesium, or thorium on tungsten, or oxide-coated surfaces.

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APPENDIX C

DERIVATION OF THE $\frac{3}{2}$ POWER LAW FOR COAXIAL CYLINDERS

In the case of concentric cylindrical electrodes the current still varies as the $\frac{3}{2}$ power of the voltage but inversely as the *first* power of the distance between

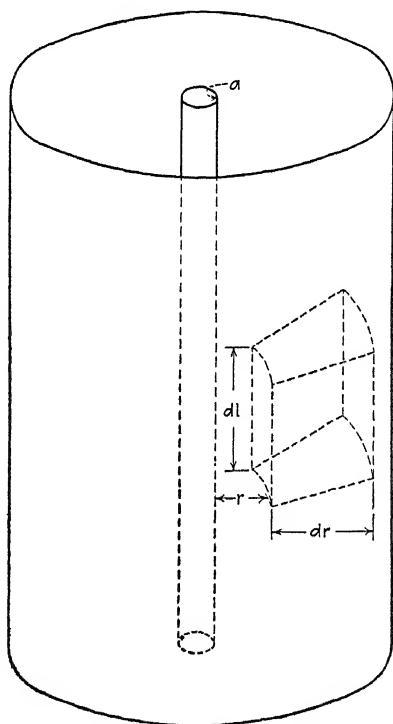


FIG. 67.

electrodes instead of inversely as the *square* of the distance, as in the case for plane-parallel electrodes. The derivation of the equation is as follows:

Let us assume a cylindrical wire cathode of radius a and length l placed in the axis of a cylindrical anode of radius r , as shown in Fig. 67. According to Gauss's theorem, the integral of the normal electric intensity over any closed surface is 4π times the charge enclosed by the surface. This is expressed by the equation

$$\iiint N ds = 4\pi \rho dx dy dz \quad (105)$$

where N = normal intensity per unit area

s = surface

ρ = charge per unit volume within the surface.

Now let us consider an element of volume in the space between the cylindrical electrodes. In this case the integral of Eq. (105) is the sum of six contributions, one from each face of the element of volume. Owing to the fact that the field is radial, the normal intensity is zero for all except the two faces $r d\theta dl$ and $(r + dr) d\theta dl$. For these two faces,

$$-N_r r d\theta dl + \left(N_r + \frac{\partial N_r}{\partial r} dr \right) (r + dr) d\theta dl = 4\pi \rho r d\theta dr dl \quad (106)$$

This reduces to

$$\frac{N_r}{r} + \frac{\partial N}{\partial r} \left(\frac{r + dr}{r} \right) = -4\pi \rho$$

or

$$\frac{N_r}{r} + \frac{dN}{dr} = -4\pi \rho \quad (107)$$

but $N = dV/dr$. Substituting this in Eq. (107),

$$\frac{l}{r} \frac{dV}{dr} + \frac{d}{dr} \left(\frac{dV}{dr} \right) = -4\pi \rho$$

or

$$\frac{d}{dr} \left(r \frac{dV}{dr} \right) = 4\pi \rho r \quad (108)$$

since ρ is negative for electrons.

In the case of cylindrical electrodes, the current density is

$$i = 2\pi r l \rho v_r \quad (109)$$

which corresponds to Eq. (61) in the case for parallel planes. As before

$$Ve = \frac{1}{2}mv^2 \quad (110)$$

Substituting Eqs. (109) and (110) in Eq. (108) we obtain

$$\frac{d}{dr} \left(r \frac{dV}{dr} \right) = i \sqrt{\frac{2m}{ve}} \quad (111)$$

This form of Poisson's equation takes the place of Eq. (64) for plane electrodes. This equation cannot be integrated directly, but Langmuir has shown the solution to be

$$i = \frac{2\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{V^{\frac{3}{2}}}{r\beta^2} \quad (112)$$

β depends upon the value of r/a and rapidly approaches unity. For all values of r/a , greater than 10, it may be taken as unity. Equation (112) then can be reduced to practical units:

$$i = 14.65 \times 10^{-6} \frac{V^{\frac{3}{2}}}{r} \text{ amp.}$$

Thus for cylindrical electrodes the space-charge-limited current varies directly as the $\frac{3}{2}$ power of the voltage and inversely as the radius of the anode.

Reference

LANGMUIR, I.: Thermionic Currents in High Vacuum, *Phys. Rev.*, **2**, 450, 1913.

CONSTANTS*

Volume occupied by 1 gram-

molecular weight of ideal gas

at 760 mm. mercury and 0°C. 22,414 cc.

Number of molecules in 1 gram-

molecular weight of gas..... 6.064×10^{23}

Charge of electron..... 4.77×10^{-10} e.s.u.

Mass of electron..... 8.994×10^{-28} g.

Planck's constant h 6.547×10^{-27} erg-sec.

Boltzmann's constant k 1.3708×10^{-16} erg per degree

Mass of hydrogen atom..... 1.6617×10^{-24} g.

* BIRGE; *Phys. Rev. Supplement*, vol. 1, No. 1, July, 1929.

PROBLEMS*

Chapter I

1. How much work is done in removing a single electron from a tungsten surface?
2. What must the velocity of an electron be in order that it may just escape from a tungsten surface?
3. What will be the thermionic emission from a unit area of a tungsten filament at the following temperatures: 2300°K. , 2400°K. , 2500°K. ? Plot these values on semilogarithmic paper.
4. At what temperature must a tungsten filament 2×10^{-3} cm. in diameter and 10 cm. long be operated in order to give 10 milliamp. emission? Use plot made in Prob. 3.
5. What must the area of a tungsten filament be in order to give 10 milliamp. emission at 2400°K. ?
6. How much would the emission from a tungsten filament be changed by a 10° change in temperature at 2400°K. ?
7. What is the ratio of the thermionic emission from nickel to that from tungsten at 1500°K. ?

Chapter II

8. The emission from a certain thoriated filament is 15×10^{-3} amp. When this filament is completely activated, its emission is 25×10^{-3} amp.; and when it is completely deactivated, it is 1×10^{-6} amp. (all measurements being made at the same temperature). What fraction of the surface is covered with thorium?
9. How large a fraction of the surface layer of thorium must be removed from a fully activated thoriated filament in order to decrease its emission 50 per cent? (The emission

*All information necessary for the solution of these problems is given in the table of constants and the various tables in the text.

from fully activated thoriated tungsten at 2000°K . is 2.864 amp. per square centimeter and for pure tungsten at the same temperature 1×10^{-3} amp. per square centimeter.)

10. Calculate the weight of thorium which would evaporate from a thoriated filament 8×10^{-3} cm. in diameter and 15 cm. long, operated at a temperature of 2000°K . for 1000 hr. The atomic weight of thorium is 232.4. What is the weight of the electrons which would be emitted by this filament in the same length of time?

11. A tungsten filament 0.02 cm. in diameter is carbonized until its conductivity is 80 per cent of the initial value. How thick is the tungsten carbide shell?

12. Calculate the values of I (emission in amperes per square centimeter) for thoriated tungsten at the following temperatures: 1200°K ., 1400°K ., 1600°K ., 1800°K ., 2000°K . Plot these values on semilogarithmic paper.

13. The work function for platinum is 6.27 volts. Calculate the value of b_0 .

Chapter IV

14. Calculate the vapor pressure of caesium at 40°C . How many atoms of caesium will strike a unit area per second at this temperature? If each of these atoms leaves the filament as a positive ion, what will be the positive-ion current from a filament having a surface of 0.1 sq. cm.?

15. What will be the electron current from a caesium-on-oxygen-on-tungsten filament having a surface of 0.2 sq. cm. at a temperature of 700°K .?

16. What will be the emission from a tungsten filament 0.2 sq. cm. in area operating at 1000°K . in caesium vapor at a bulb temperature of 50°C .?

Chapter VI

17. What is the total amount of energy radiated from a tungsten filament 0.01 cm. in diameter and 10 cm. long at 2000°K .?

a. Use the fourth-power law.

b. Use Worthing and Forsythe's empirical formula.

c. What will be the resistance of this filament at this temperature?

d. What current will be required to maintain this temperature, and what will be the voltage drop across the filament?

18. A current of 1.45 amp. will heat a 4-mil tungsten filament to a temperature of 2400°K . What current will be required to heat an 8-mil filament to the same temperature?

19. The resistance of a 50-watt incandescent tungsten filament lamp operating at 2685°K . is 288 ohms. What is its resistance at 20°C .?

20. In order to give the proper value of emission for a certain vacuum tube, a thoriated filament having an area of 0.3 sq. cm. operating at a temperature of 2000°K . must be used. The desired filament drop is 5 volts. What are the filament dimensions and what will be the current?

21. The emission from a tungsten filament 4 mils in diameter and 15 cm. long, heated by a current of 1.25 amp., is 7×10^{-3} amp. What would the emission be if there were no lead losses? (Assume leads to be at room temperature.)

Chapter VII

22. The rate of evaporation of tungsten at 2500°K . is 9.18×10^{-10} g. per square centimeter per second. How long would a 5-mil filament run at this temperature before burning out? The density of tungsten is 19.3 g. per cubic centimeter.

Chapter VIII

23. What is the maximum electron current which can be drawn from a small filament 3 cm. long to an anode 1.5 cm. in diameter in a high vacuum at 180 volts? How much would the anode voltage have to be increased in order to double this current?

24. What is the maximum positive-ion current that could be carried by caesium atoms from a small filament 3 cm. long to an anode 1.5 cm. in diameter at 180 volts? (The atomic weight of caesium is 132.8.)

25. What fraction of the electrons emitted from a tungsten filament at 2300°K . can move against a retarding field of 2 volts?

Chapter IX

26. The resonance potential of mercury is 4.9 volts. How much work does an electron do in exciting a mercury atom to its resonance potential? What are the frequency and the wave length of the radiation emitted by the atom in returning to its normal condition?

27. The resonance line of sodium is 5893 Å. What is the velocity of the electrons necessary to excite this radiation?

28. What is the mean free path of electrons passing through mercury vapor at room temperature? ($\sigma = 1.5 \times 10^{-8}$ cm. The vapor pressure of mercury is 1.3×10^{-3} mm. at 20°C.)

29. The positive-ion current to a plane electrode 1 sq. in. in a discharge in mercury vapor is 10×10^{-3} amp. when the electrode is at a potential of minus 80 volts. What is the thickness of the positive-ion sheath?

Chapter X

30. The arc drop in a certain Thyatron is 10 volts. The tube is operated on a sine voltage having a peak value of 110 volts. The series load resistance is 100 ohms. What is the current when the grid and anode voltage are in phase? When the grid voltage is lagging 120° behind the anode voltage?

Chapter XI

31. The work function for tungsten is 4.52 volts. What is the photoelectric long-wave limit for tungsten?

32. A certain photoelectric cell gives a current of 4×10^{-3} amp. per watt of incident energy of radiation of wave length 5893 Å. Express this in terms of number of electrons per 100 incident quanta.

33. The sensitivity of a certain photoelectric cell is 40×10^{-6} amp. per lumen. A 60-watt vacuum lamp has a mean horizontal candle power of 60. What will be the photoelectric current if the photoelectric cell is 3 ft. from the lamp and the aperture of the cell is 1 in. in diameter?

ANSWERS TO PROBLEMS

1. 7.18×10^{-12} erg
2. 1.27×10^8 cm. per second
3. 3.5×10^{-2} amp. per square centimeter at 2300°K .
 1.1×10^{-1} amp. per square centimeter at 2400°K .
 2.58×10^{-1} amp. per square centimeter at 2500°K .
4. 2450°K .
5. 0.1 sq. cm.
6. 9.96 per cent
7. 7.9×10^5
8. 0.95
9. 0.09
10. 7.97×10^{-7} g. of thorium
 2.2×10^{-2} g. of electrons
11. 0.0014 cm.
12. 3.95×10^{-5} amp. per square centimeter at 1200°K .
 2.03×10^{-3} amp. per square centimeter at 1400°K .
 4.06×10^{-2} amp. per square centimeter at 1600°K .
 4.28×10^{-1} amp. per square centimeter at 1800°K .
2.86 amp. per square centimeter at 2000°K .
13. $72,500^\circ\text{K}$.
14. 6.2×10^{-3} barye
 1.04×10^4 atoms per second
 1.65×10^{-16} amp.
15. 0.35×10^{-3} amp.
16. 50 amp.
17. a. 24.0 watts
b. 24.2 watts
c. 1.8 ohms
d. 3.69 volts
18. 4.1 amp.
19. 20.16 ohms
20. 7.47 cm. long
0.0128 cm. in diameter
1.44 amp.
21. 16.45×10^{-3} amp.
22. 140 hr.
23. 0.1415 amp.
285 volts
24. 0.287×10^{-3} amp.
25. 4.5×10^{-5}
26. 7.75×10^{-12} erg
 1.18×10^{15} vibrations per second
2536 Å.
27. 2.1 volts
28. 30.7 cm.
29. 1.65×10^{-2} cm.
30. 0.32 amp.
0.239 amp.
31. 2730 Å.
32. 1.7×10^{-2} electron per 100 quanta
33. 1.46×10^{-6} amp.

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